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Technical Report

GAMMA-RAY STREAMING THROUGH DUCTS

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U. S. NAVAL CIVIL ENGINEERING LABORATORY

Port Hueneme, California

GAMMA-RAY STREAMING THROUGH DUCTS

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Type C

by

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ABSTRACT

A survey is presented of the current status of experimental and theoretical investigations of the problem of gamma-ray streaming through air ducts in concrete. Data are tabulated and plotted for a variety of experiments. Comparisons are made between theory and experiment, inconsistencies are pointed out, and areas needing further investigation are indicated.

INTRODUCTION

In the shielding of personnel against gamma radiation from nuclear weapons, an important aspect of the problem is consideration of the hazard caused by radiation which is scattered off interior surfaces of entranceways and air ducts into the shelter area. The duct streaming problem has been investigated both experimentally and theoretically at several laboratories. Current understanding of the problem has progressed to the stage where a review of progress to date is indicated. This report purposes to survey this information.

Section I will describe some experimental determinations of the attenuation of gamma-ray dose within concrete ducts as a function of distance from the radioactive source. Section II will be concerned with albedo, which is an important concept in gamma-ray scattering. Section III will describe theoretical approaches to the duct streaming problem. The figures, presenting plotted and tabulated data, follow the text.

I. EXPERIMENTAL INVESTIGATIONS

Several investigators have conducted experiments giving information on the distribution of radiation along the axis of air ducts in concrete with square, rectangular, and round cross sections. Some of the ducts have one right-angle bend, and some have two right-angle bends. In every case treated here the measurements were made with a gamma-ray point source.

The significant results of these investigations will be discussed and compared with each other and with theory. A systematic effort will be made to give as much information as is available on actual experimental results so that the data may be convenient to other investigators.

Definition of Terms

A uniform terminology is used for the various sources of data:

D = measured dose rate in mr/hr at some distance along the axis of the duct

D_o = dose rate in mr/hr at 1 foot from source in air

L   = total length of the duct in feet as measured along the axis; i.e.,
       $L = L_1 + L_2$ for a two-legged duct, and $L = L_1 + L_2 + L_3$ for a
       three-legged duct

L_1 = length of first leg in feet, measured from the point source on the axis
       to the center of the first corner

L_2 = length of second leg in feet, measured from the center of the first
       corner to the end of the duct in the case of a two-legged duct, or
       from the center of the first corner to the center of the second corner
       in the case of a three-legged duct

T   = the distance in feet from the source to a point on the axis measured
       along the axis of the duct

W/2 = half-width of duct in feet: for a square, W/2 is half of the width of
       a side of the cross section of the duct; for a rectangle, W/2 is the
       geometric mean of the half-height and half-width of the duct (i.e.,
       W^2 is the area of the cross section of the duct); for a round cross
       section with radius R, W/2 is given by $W/2 = \sqrt{\pi}R/2$ (i.e., W^2 is
       the area of the cross section of the duct)

L-shape refers to a duct with a single right-angle bend.

U-shape refers to a duct with two right-angle bends of the same sense, so that
       radiation reaching the detector streams in the opposite direction to
       radiation streaming from the source down the first leg.

Z-shape refers to a duct with two right-angle bends of opposite sense, such
       as a tunnel with an offset.

Experimental Findings

   Eisenhauer.   The scattering of Co^{60} gamma radiation in square and rectangular
air ducts in concrete was investigated experimentally by Eisenhauer.[1] He measured
dose rates along the axis of the second leg of a two-legged duct, and along the axis
of the third leg of a three-legged duct.   Results are plotted and tabulated in
Figures 1 through 5.

   Eisenhauer found that the dose rate along the axis of the second leg of a
two-legged duct varied as the inverse cube of the distance along the second leg.
Also, he demonstrated the importance of scattering from the inside corner of the
first right-angle junction.   He made some "trapping" experiments by setting back
one of the walls in a corner junction.

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Terrell. Extensive experimental investigations of gamma-ray streaming through air ducts in concrete have been carried out by Terrell and his co-workers at the Armour Research Foundation.[2,3,4] Results are shown in Figures 6 through 23. This series of studies included Co^{60}, Cs^{137}, Na^{24}, and Au^{198}. All ducts had square cross sections, some 6 x 6 feet and some 1 x 1 foot. Some of the ducts had one right-angle bend, and some had two right-angle bends.

Terrell[3] investigated the relative importance of scattering from the walls and ceiling at a corner, both by covering surface areas with lead (which has a much lower gamma-ray albedo than does concrete) and by removing walls.

Experiments with U-shaped and Z-shaped ducts[4] showed that the sense of the second right-angle bend is not a significant factor, at least as long as the axes of all three legs of a duct lie in the same plane.

Green. An experimental study of the streaming of the gamma radiation of Co^{60} in an 11-inch square duct with one right-angle bend led Green[5] to three principal conclusions:

1. Trapping the corner surfaces of a duct is not generally an economically feasible means for improving attenuation factors.

2. Dose-rate contributions due to multiple scatter represent a significant contribution to total dose rate at the detector.

3. Dose rate falls off as the inverse square of axial distance along the first leg of a duct and almost as the inverse cube along the axis of the second leg.

Results of Green's measurements are shown in Figures 24 and 25.

Chapman. Dose-rate measurements and gamma-ray spectrum measurements were made inside a square concrete duct with a 3 x 3-foot cross section.[6] By measuring the energy spectra of gamma rays scattered from particular surface elements, Chapman was able to demonstrate the importance of multiple scatter. He showed that, at some places within a duct, dose contributions due to multiple scatter can be of the same magnitude as the dose contribution due to single scatter. Results of Chapman's duct-streaming measurements are presented in Figures 26 and 27.

Fowler and Dorn. Measurements were made of dose attenuation along the axis of a three-legged duct having a circular cross section.[7] Results are presented in Figures 28 and 29. It was shown that, except for minor differences, a round duct attenuates gamma radiation in much the same way as a square duct of the same cross-sectional area.

Jacovitch and Chapman. J. M. Chapman of NCEL is working on an
experimental study initiated by J. Jacovitch of the possibility of a gamma-ray
polarization effect which may improve the protection afforded by a three-legged
duct if one of the legs is noncoplanar with the other two. The problem was suggested
by L. V. Spencer, who pointed out that a gamma-ray photon is unlikely to scatter
out of its plane of polarization. It is not clear whether gamma-ray polarization
will be important in the crude geometry of a concrete duct. Experimental results
are not yet available.

Review of Experimental Findings

Figures 30 and 31 are composite plots of all the data of Figures 1 through 29.
There are several reasons why one would expect wide dispersion in the data:

   1. Several different initial energies were used.

   2. Some ducts had two legs and some had three.

   3. Several different widths were used.

   4. Several different lengths were used.

Despite all the reasons given above, it can be seen from Figures 30 and 31
that dose tends generally to fall off exponentially with T/L. Clearly, such an
exponential decay cannot be true for both very short (L $\approx$ W) and very long
(L $>>$ W) ducts. The reason for the apparent $e^{-T/L}$ behavior is presumably that
most experimenters chose leg lengths equal to a few (~3) duct diameters.

Efforts have been made at NCEL to find an empirical expression relating
dose to such factors as number of legs, lengths of legs, initial energy, and duct
width. No reasonable expression with acceptable accuracy has yet been found.
A relatively simple formula needs to be found before useful criteria can be specified
for designers.

II. ALBEDO

Theory

An important concept in gamma-ray scattering is "albedo," or reflection.
The term "differential dose albedo" is discussed by Rockwell[8] and by Chilton and
Huddleston.[9] The definition of differential dose albedo will be reproduced here
since it will be important to theoretical arguments which will follow. The scat-
tering of radiation from a point source incident on a slab is diagramed as follows.
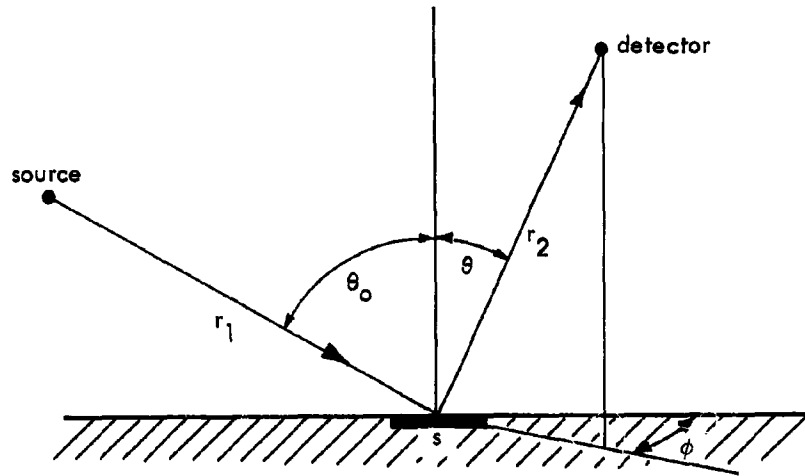
For such a case the differential dose albedo α is defined by the equation

$$dD = \frac{D_1 \alpha (E_o, \theta_o, \theta, \varphi) \cos \theta_o \, dA}{r_1^2 r_2^2} \qquad (1)$$

where dD = differential dose at point of measurement

D_1 = dose in air at unit distance from source

E_o = energy of incident radiation

θ_o = polar angle of incidence of radiation

θ = polar angle of backscattered radiation

φ = azimuthal angle of backscattered radiation

dA = differential area of scattering surface

r_1 = distance from source to dA

r_2 = distance from dA to detector

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It is seen that α may be a function of E_o and of the three angles: θ_o, θ, and φ, where α can be thought of as a coefficient of dose reflection.

From Equation 1 and the diagram it is clear that the dose from the source incident per unit area at dA is $D_1 \cos\theta_o / r_1^2$. If the incident radiation is a broad parallel beam incident on a semi-infinite plane slab, the radiation intensity per unit area at dA becomes $D_o \cos\theta_o$, where D_o is the dose measured in the incident beam. Equation 1 then becomes

$$ dD = \frac{D_o \alpha \cos\theta_o \, dA}{r_2^2} \tag{2} $$

Differential dose albedo, as used here, will be the quantity α as defined by Equation 2.

Attempts have been made to determine α as a function of angles and incident energy. Monte Carlo techniques,[10,11,12,13] analytical approaches,[14] and experimental measurements[15,16] have all been used to determine α.

Raso[11] performed Monte Carlo calculations for a broad, parallel monoenergetic beam of gamma rays incident on a semi-infinite slab of concrete. From backscattering histories, differential dose albedo was computed as a function of initial energy, polar angle of incidence, and polar and azimuthal angles of reflection. Using Raso's data, Chilton and Huddleston[9] developed a semiempirical formula for the differential dose albedo of gamma rays on concrete. The formula can be expressed as

$$ \alpha = \frac{C K(\theta_s) 10^{26} + C'}{1 + \dfrac{\cos\theta_o}{\cos\theta}} \tag{3} $$

where $K(\theta_s)$ is the Klein-Nishina differential energy-scattering cross section; C and C' are parameters dependent on the initial energy, E_o; and α, θ_o, and θ are as previously defined. θ_s is the spacial angle of gamma-ray scatter.

The parameters for the energies considered by Raso are shown below:

E_o (Mev)	C	C'
.2	.0221 ± .0018	.0356 ± .0033
.5	.0336 ± .0016	.0220 ± .0012
1	.0547 ± .0020	.0111 ± .0007
2	.0869 ± .0027	.0077 ± .0004
4	.1238 ± .0046	.0076 ± .0003
6	.1490 ± .0065	.0075 ± .0003
10	.1660 ± .0084	.0070 ± .0002

The values were obtained by fitting the data of Raso to Equation 3 by a least-squares method.

Experimental Investigation

The U. S. Naval Radiological Defense Laboratory has made experimental measurements of the differential angular backscatter of gamma-ray doses from thick slabs of steel, aluminum, and concrete, using radioactive sources of Co^{60} and Cs^{137}. Although final results of the NRDL study are not yet available, preliminary results reported to NCEL indicate fair agreement with the results of Raso.

Uses of the Theory

The semiempirical formula of Equation 3 has been used by Chilton[17] to calculate the backscatter by an infinite concrete slab of the radiation from isotropic point sources of Na^{24}, Co^{60}, Cs^{137}, and Au^{198}. Agreement was found with the experimental results of Clarke and Batter[18] within the limits of experimental error.

Another test and use of Equation 3 is in the calculation of gamma-ray dose attenuation along the axis of a two-legged rectangular duct. Chapman[19] has found that the semiempirical formula can be used to calculate dose attenuation in a concrete duct. Chapman compares his calculated results with the experimental results tabulated in Figures 1 through 29. He finds agreement within 30 percent in all cases except for the Au^{198} data, where the calculated results are about a factor of 2 higher than the experimental results.

The theory indicates that protection factors (which are the reciprocals of the D/D_o attenuation factors) should decrease as the energy of the gamma-ray source decreases. Therefore, among the various sources experimentally investigated, the greatest protection factor should obtain for Na^{24}, while the protection factor for

Au^{198} should be the smallest, provided the duct geometry is the same in all cases. However, experimental results[3] indicate a larger protection factor for Au^{198} radiation than for Cs^{137} radiation. Further experimental study of the streaming of Au^{198} gamma radiation through concrete ducts should be undertaken to resolve the "gold anomaly."

A Simplification of the Albedo Problem

It has been shown by Shoemaker and Huddleston[20] that variations in the azimuthal angle φ are redundant in experimental measurements of differential dose albedo provided that Equation 3 or a generalization of Equation 3 is valid. Once differential dose albedo has been determined for a complete set of incident and reflected polar angles with zero azimuth, albedo at any azimuth is shown to be calculable by a suitable mathematical transformation.

III. THEORY OF DUCT STREAMING

Most treatments of the streaming of gamma radiation through air ducts in concrete are based on the method of LeDoux and Chilton.[21] They considered backscattered radiation from those areas within a two-legged duct which could be "seen" by both the source and the detector. They also considered in-scatter by the inside corner lip at the intersection of the two legs. Results generally gave good qualitative agreement with experiment, but theoretical predictions were low because of neglect of multiple-scatter contributions.

Green[5] demonstrated the importance of multiple scatter. Silverman[22] indicated how second scatter could be computed, although he did not actually carry out the calculations. Ingold[23] computed second-scatter contributions within a straight cylindrical duct. Chapman,[19] using the albedo concept and an extension of the LeDoux-Chilton method, calculated dose attenuations for gamma rays of various energies in two-legged concrete ducts of various sizes.

With the geometry of rectangular ducts it should be possible to use the ADONIS[24] computer code for calculating gamma-ray dose attenuation. Efforts are currently underway at NCEL to perform such calculations. ADONIS is an IBM-7090 Monte Carlo computer code which can compute the neutron or gamma-ray dose anywhere within a configuration composed of rectangular parallelepipeds. Such a code is expected to be useful for calculations of dose rates within ducts.

CONCLUSION

The status of the gamma-ray streaming problem is such that current theory accounts for almost all observed results. Although the problem is by no means solved, important advances of recent years have greatly added to our understanding.

The corresponding problem for neutrons is not nearly so well understood. Increased emphasis should be placed on neutron work in the future.

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Attenuation Factor D/D$_o$ (D_o = 8520 mr/hr)

1

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}

$\leftarrow L_1/L \rightarrow$
L_1 = 3.28 ft

$\leftarrow L_2/L \rightarrow$
L_2 = 3.28 ft
(assumed)

Axial Distance (ft)	Observed Dose Rate (mr/hr)
3.28	1155
3.76	142
3.93	75.0
4.09	49.0
4.25	33.0
4.58	14.9
4.88	8.40
4.91	7.80
5.21	4.80
5.24	4.40
5.53	3.04
5.86	2.07
6.19	1.46

1/L

0   .1   .2   .3   .4   .5   .6   .7   .8   .9   1.0

Ratio T/L   (L = 6.56 ft)

Figure 1. L-shaped 0.630 x 0.952-foot rectangular concrete duct with W/2 = 0.3815 foot; 0.6-curie Co^{60} point source. (From Reference 1, supplemented by correspondence.)
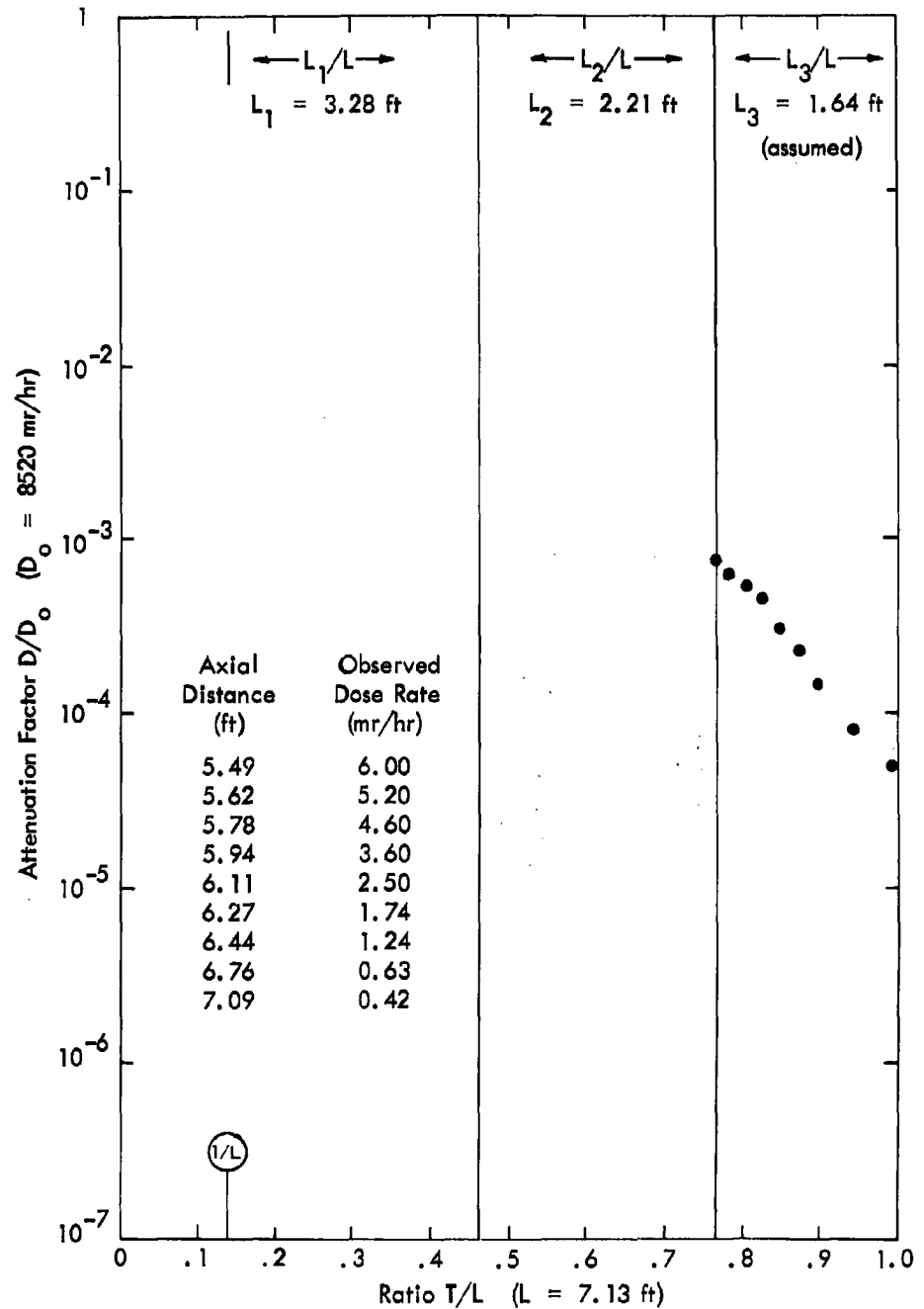
Figure 2. U-shaped 0.925 x 0.925-foot square concrete duct with W/2 = 0.4625 foot; 0.6-curie Co⁶⁰ point source. (From Reference 1, supplemented by correspondence.)

The figure shows an axial distance table and a plot of Attenuation Factor D/D_o ($D_o = 8520$ mr/hr) versus Ratio T/L (L = 7.13 ft):

Axial Distance (ft)	Observed Dose Rate (mr/hr)
5.49	6.00
5.62	5.20
5.78	4.60
5.94	3.60
6.11	2.50
6.27	1.74
6.44	1.24
6.76	0.63
7.09	0.42

Plot labels: L_1/L, $L_1 = 3.28$ ft; L_2/L, $L_2 = 2.21$ ft; L_3/L, $L_3 = 1.64$ ft (assumed).

13

Figure 2. U-shaped 0.925 x 0.925-foot square concrete duct with W/2 = 0.4625 foot; 0.6-curie Co⁶⁰ point source. (From Reference 1, supplemented by correspondence.)

13
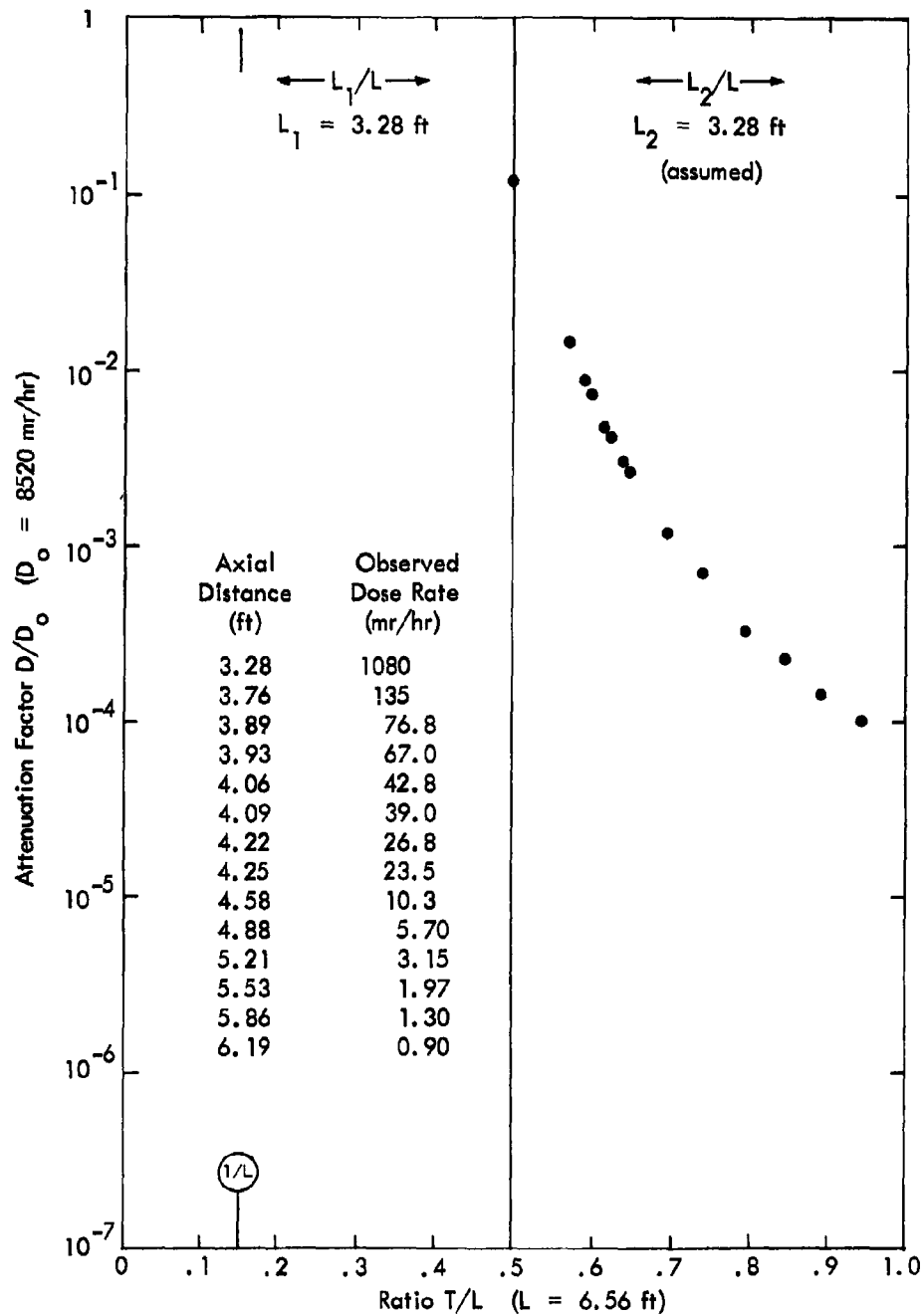
Figure 3. L-shaped 0.630 x 0.630-foot square concrete duct with W/2 = 0.3149 foot; 0.6-curie Co^{60} point source. (From Reference 1, supplemented by correspondence.)

14
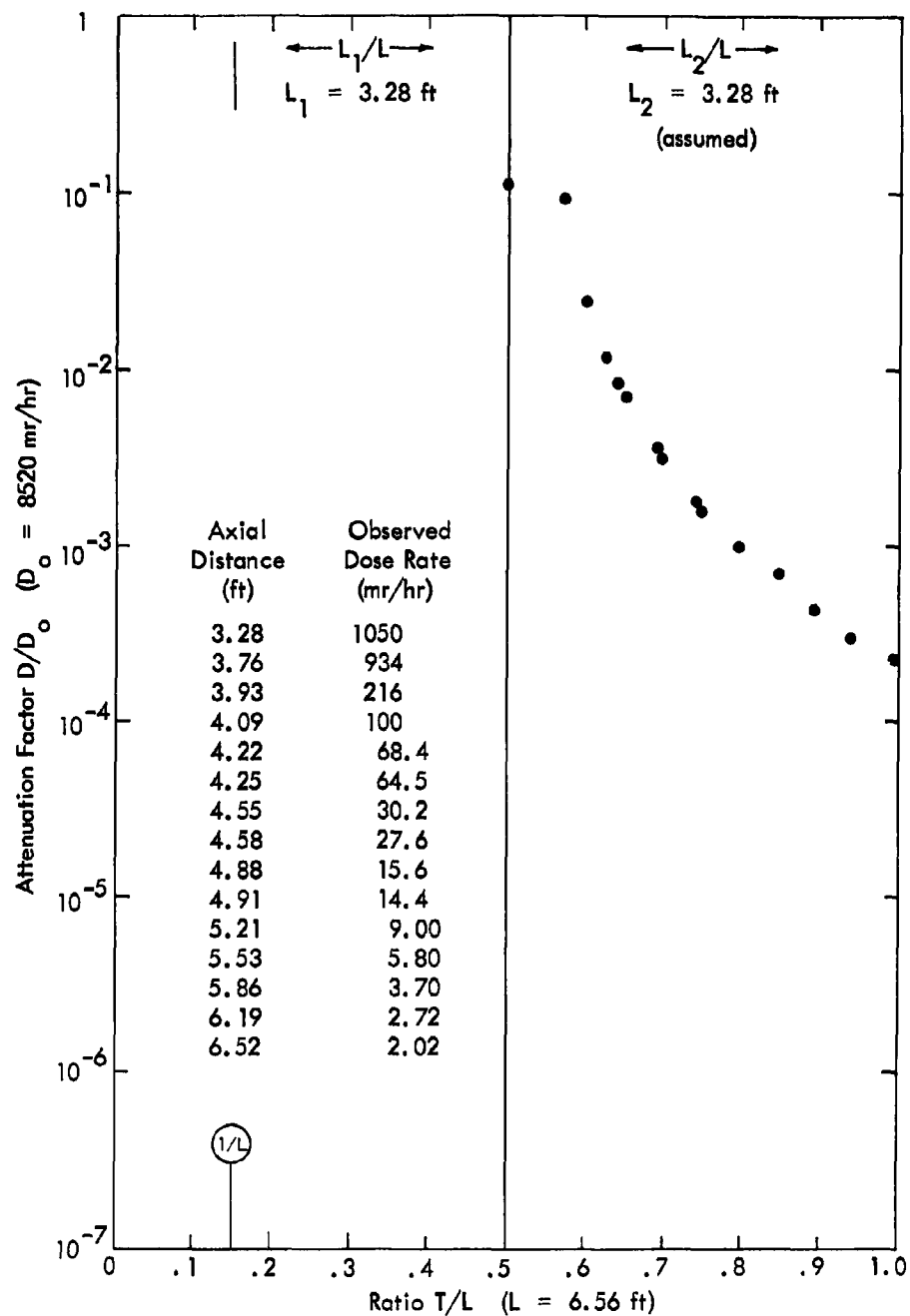
Figure 4. L-shaped 0.925 x 0.925-foot square concrete duct with W/2 = 0.4625 foot; 0.6-curie Co[60] point source. (From Reference 1, supplemented by correspondence.)

The chart contains the following labeled data table:

Axial Distance (ft)	Observed Dose Rate (mr/hr)
3.28	1050
3.76	934
3.93	216
4.09	100
4.22	68.4
4.25	64.5
4.55	30.2
4.58	27.6
4.88	15.6
4.91	14.4
5.21	9.00
5.53	5.80
5.86	3.70
6.19	2.72
6.52	2.02

Axis labels: Attenuation Factor D/D_o (D_o = 8520 mr/hr); Ratio T/L (L = 6.56 ft)

L_1/L, L_1 = 3.28 ft; L_2/L, L_2 = 3.28 ft (assumed)

15
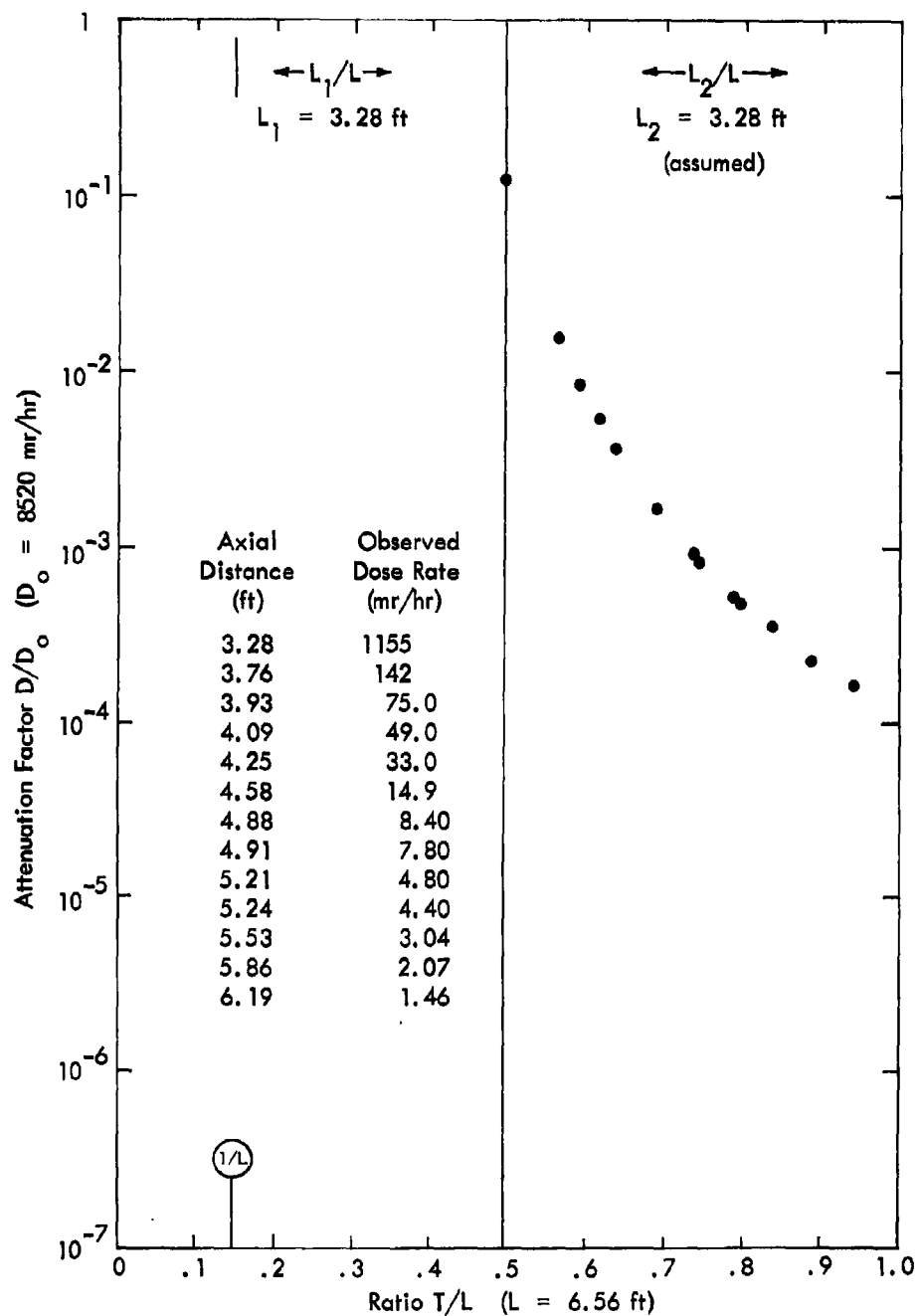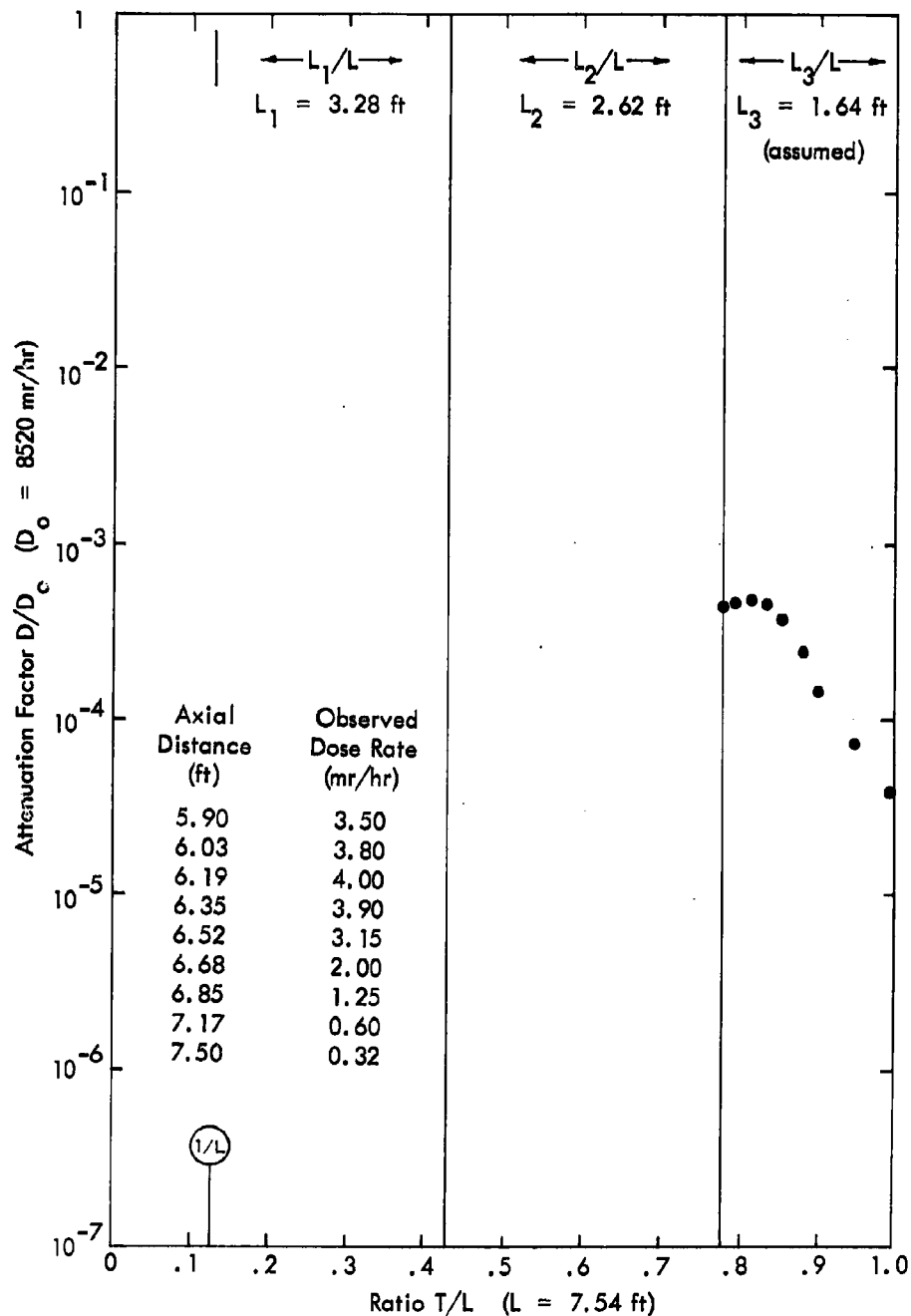
Figure 5. Z-shaped 0.925 × 0.925-foot square concrete duct with W/2 = 0.4625 foot; 0.6-curie Co[60] point source. (From Reference 1, supplemented by correspondence.)
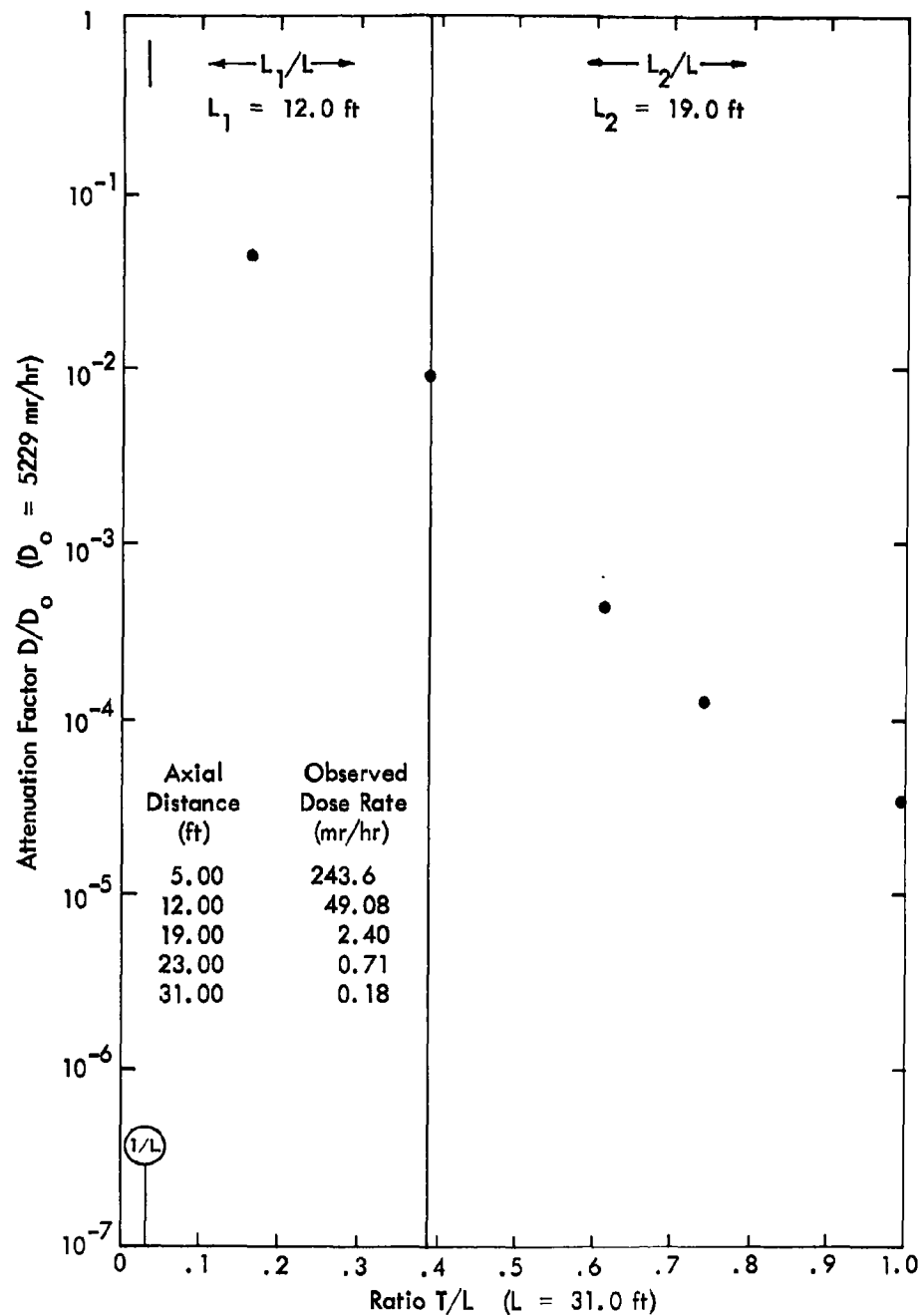
Figure 6. L-shaped 6 x 6-foot concrete entranceway with $W/2 = 3.0$ feet; 1.52-curie Cs^{137} point source. (From Reference 2, Table 4.)
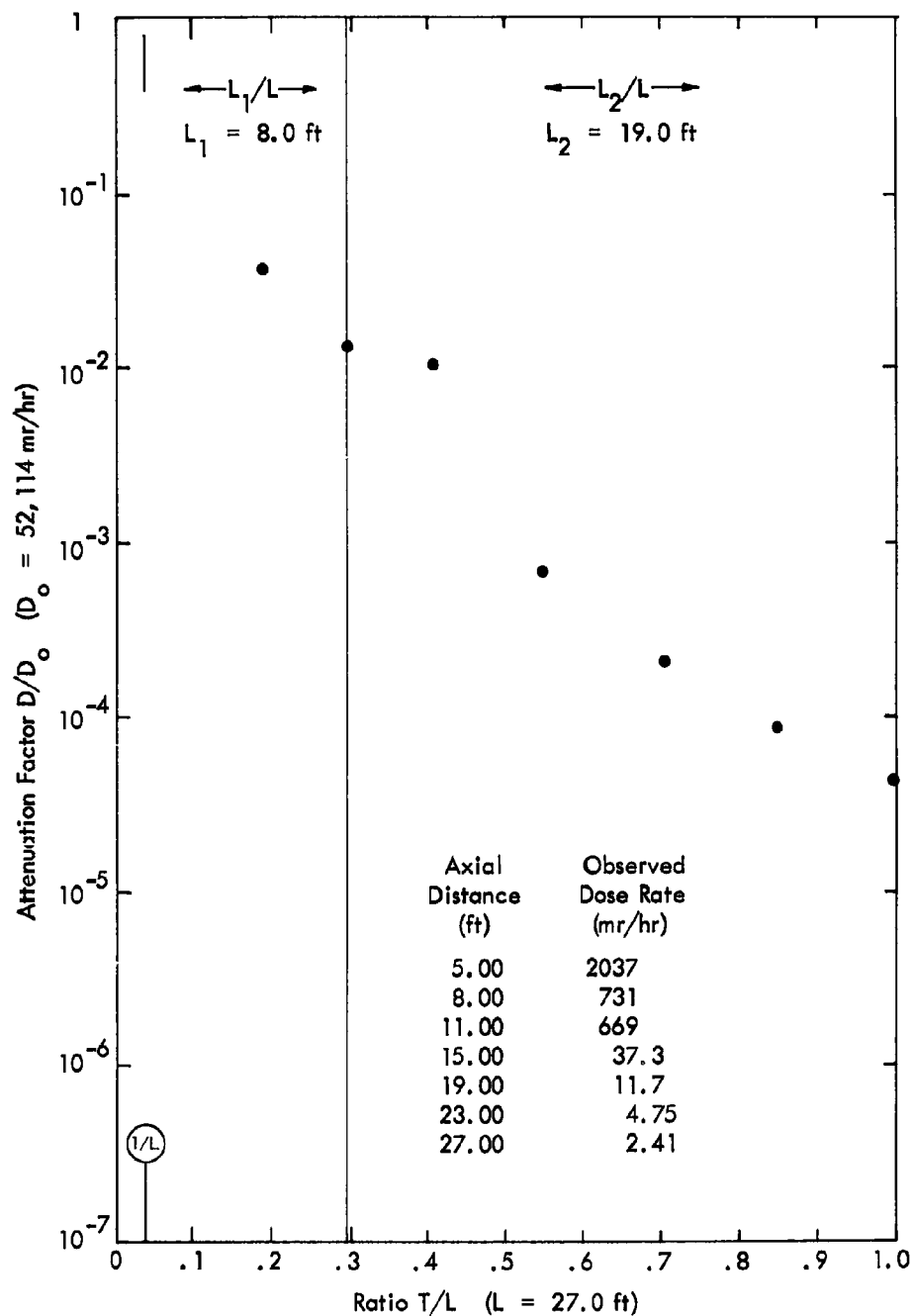
Figure 7. L-shaped 6 x 6-foot concrete entranceway with
W/2 = 3.0 feet; 3.67-curie Co^{60} point source.
(From Reference 2, Table 5A.)

The chart shows:
- Y-axis: Attenuation Factor D/D$_o$ (D_o = 5214 mr/hr), ranging from 10^{-7} to 1
- X-axis: Ratio T/L (L = 29.0 ft), ranging from 0 to 1.0
- Top region labels: L$_1$/L with L$_1$ = 10.0 ft; L$_2$/L with L$_2$ = 19.0 ft
- 1/L marker at bottom left

Axial Distance (ft)	Observed Dose Rate (mr/hr)
7.00	1065
10.00	462
13.00	465
17.00	21.96
21.00	7.29
25.00	2.73
29.00	1.38

Figure 8. L-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 3.67-curie Co[60] point source. (From Reference 2, Table 5B.)

19
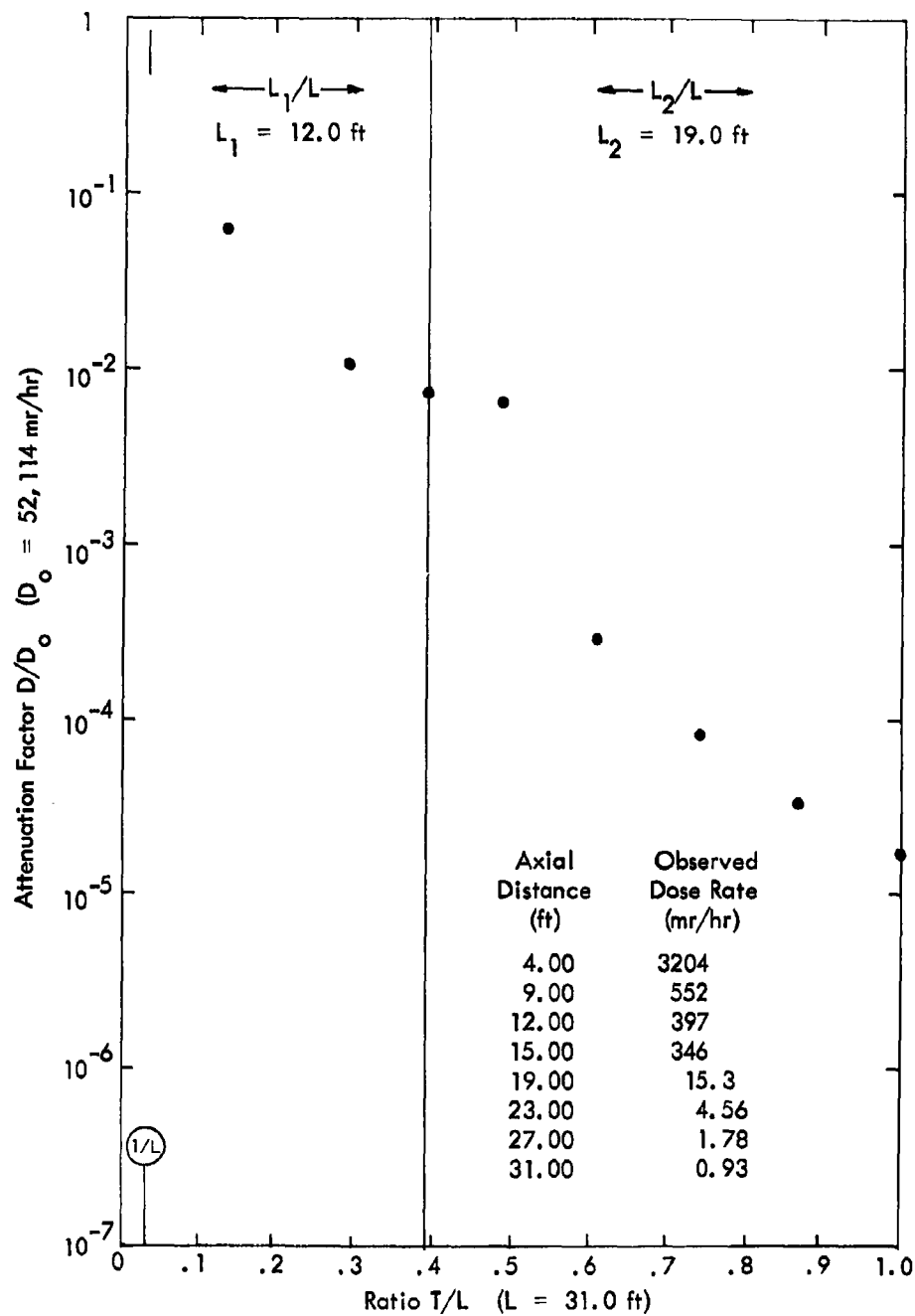
Figure 9. L-shaped 6 x 6-foot concrete entranceway with
W/2 = 3.0 feet; 3.67-curie Co^{60} point source.
(From Reference 2, Table 5C.)

20

Attenuation Factor D/D$_o$ (D$_o$ = 83,160 mr/hr)

Ratio T/L   (L = 36.0 ft)

← L$_2$/L →
L$_2$ = 19.0 ft

← L$_1$/L →
L$_1$ = 17.0 ft

| Axial Distance (ft)	Observed Dose Rate (mr/hr)
2.00	18000
3.00	8760
5.00	3306
8.00	1332
11.00	744
14.00	474
15.50	399
17.00	330
18.50	327
20.00	300
21.00	43.6
22.00	16.5
23.00	9.84
24.00	6.30
28.00	1.93
32.00	0.82
34.00	0.63
36.00	0.46
37.00	0.40

Figure 10.   L-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 4.2-curie Na^{24} point source. (From Reference 3, Table 1.)

21
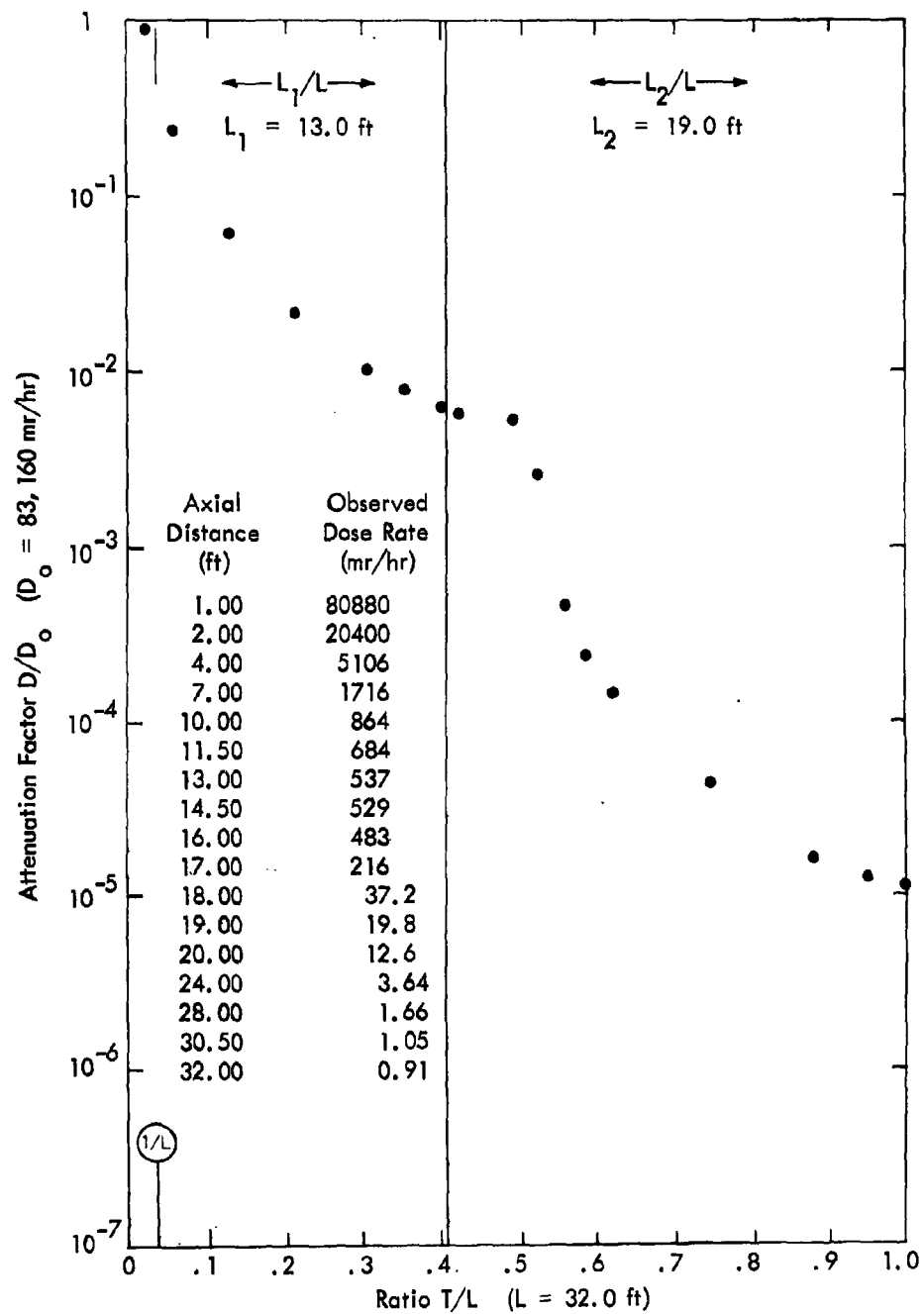
Figure 11. L-shaped 6 x 6-foot concrete entranceway with
W/2 = 3.0 feet; 4.2-curie Na^{24} point source.
(From Reference 3, Table 2.)

The axial distance and observed dose rate data shown in the figure:

Axial Distance (ft)	Observed Dose Rate (mr/hr)
1.00	80880
2.00	20400
4.00	5106
7.00	1716
10.00	864
11.50	684
13.00	537
14.50	529
16.00	483
17.00	216
18.00	37.2
19.00	19.8
20.00	12.6
24.00	3.64
28.00	1.66
30.50	1.05
32.00	0.91

The attenuation factor plot with axes: Y-axis "Attenuation Factor D/D_o (D_o = 83,160 mr/hr)" ranging from 10^{-7} to 1; X-axis "Ratio T/L   (L = 29.0 ft)" from 0 to 1.0.

Labels on plot: L_1/L with L_1 = 10.0 ft; L_2/L with L_2 = 19.0 ft; circled 1/L.

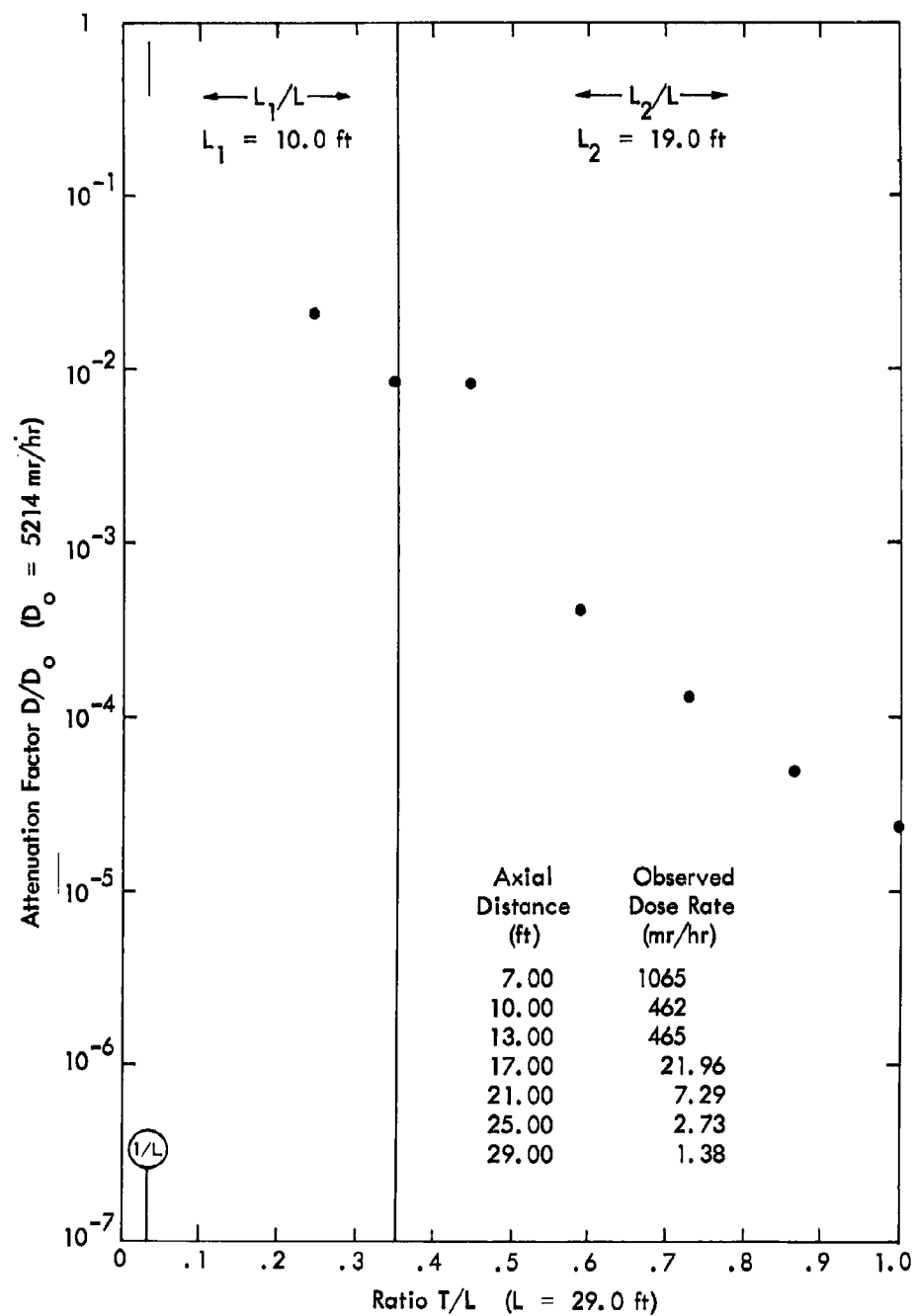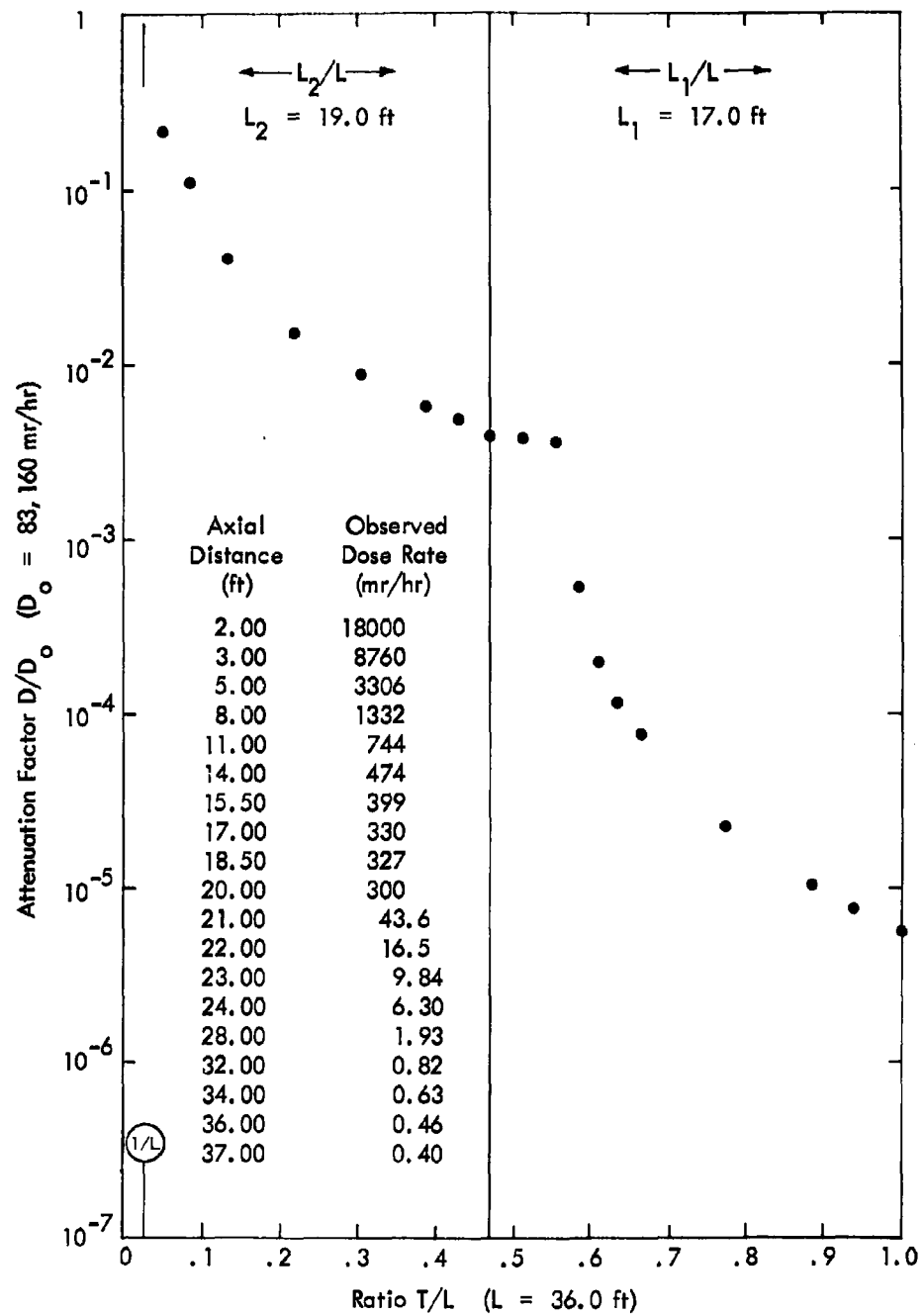| Axial Distance (ft)	Observed Dose Rate (mr/hr)
1.00	79320
2.00	20400
4.00	5016
7.00	1698
8.50	1188
10.00	882
11.50	852
13.00	774
14.00	708
15.00	85.2
16.00	39.6
17.00	25.3
21.00	6.78
25.00	2.80
27.00	2.45
29.00	1.50

Figure 12.   L-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 4.2-curie Na^{24} point source. (From Reference 3, Table 3.)
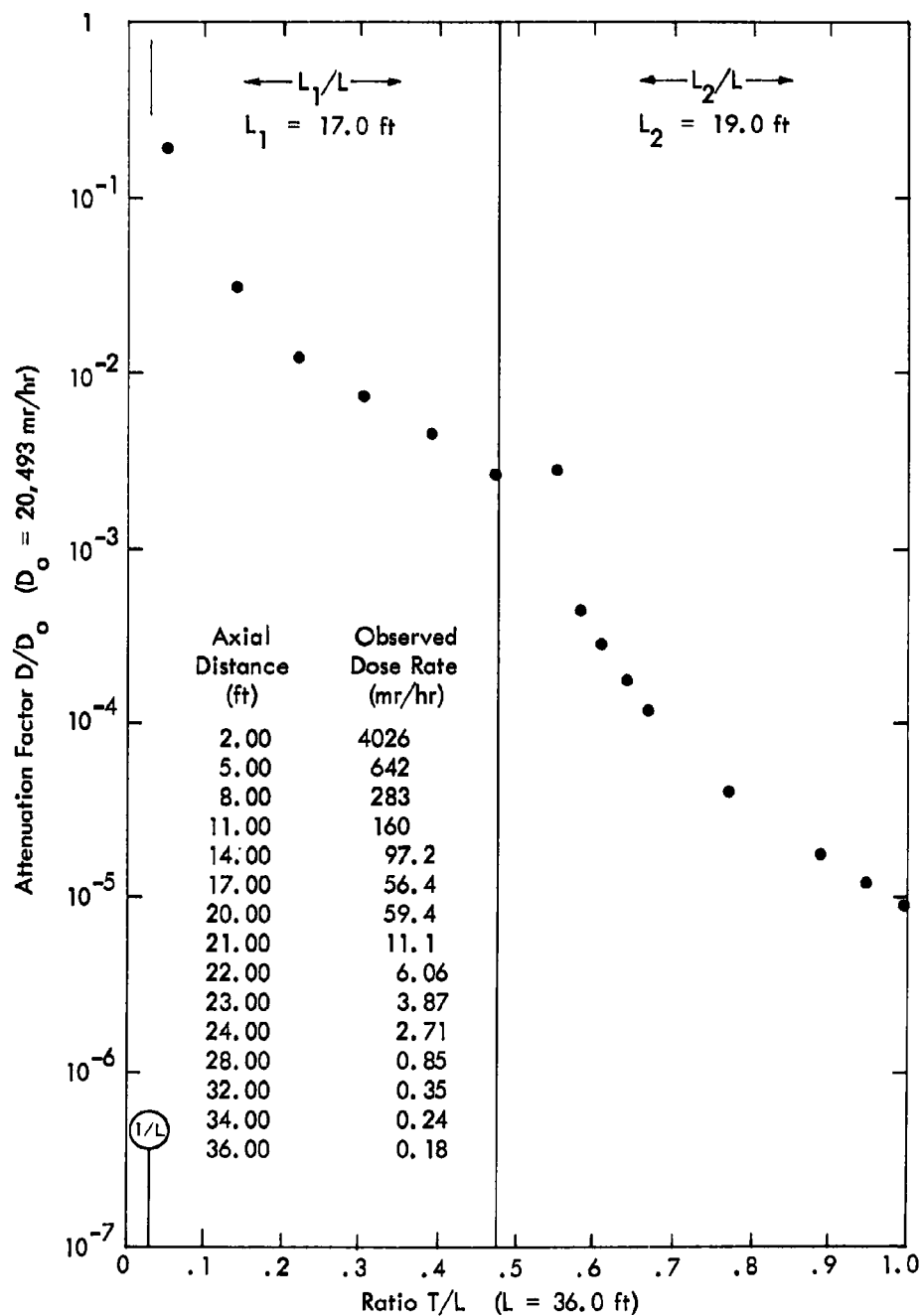
Figure 13. L-shaped 6 x 6-foot concrete entranceway with
W/2 = 3.0 feet; 8.1-curie Au[198] point source.
(From Reference 3, Table 4.)

Axial Distance (ft) / Observed Dose Rate (mr/hr):

Axial Distance (ft)	Observed Dose Rate (mr/hr)
2.00	4062
4.00	924
7.00	229
10.00	182
13.00	112
16.00	97.2
17.00	35.7
18.00	13.6
19.00	9.00
20.00	5.19
24.00	1.66
28.00	0.71
30.00	0.56
32.00	0.36

Y-axis: Attenuation Factor D/D_o (D_o = 20,493 mr/hr)

X-axis: Ratio T/L (L = 32.0 ft)

L_1/L, L_1 = 13.0 ft L_2/L, L_2 = 19.0 ft

1/L

Figure 14. L-shaped 6 x 6-foot concrete entranceway with
W/2 = 3.0 feet; 8.1-curie Au^{198} point source.
(From Reference 3, Table 5.)

25
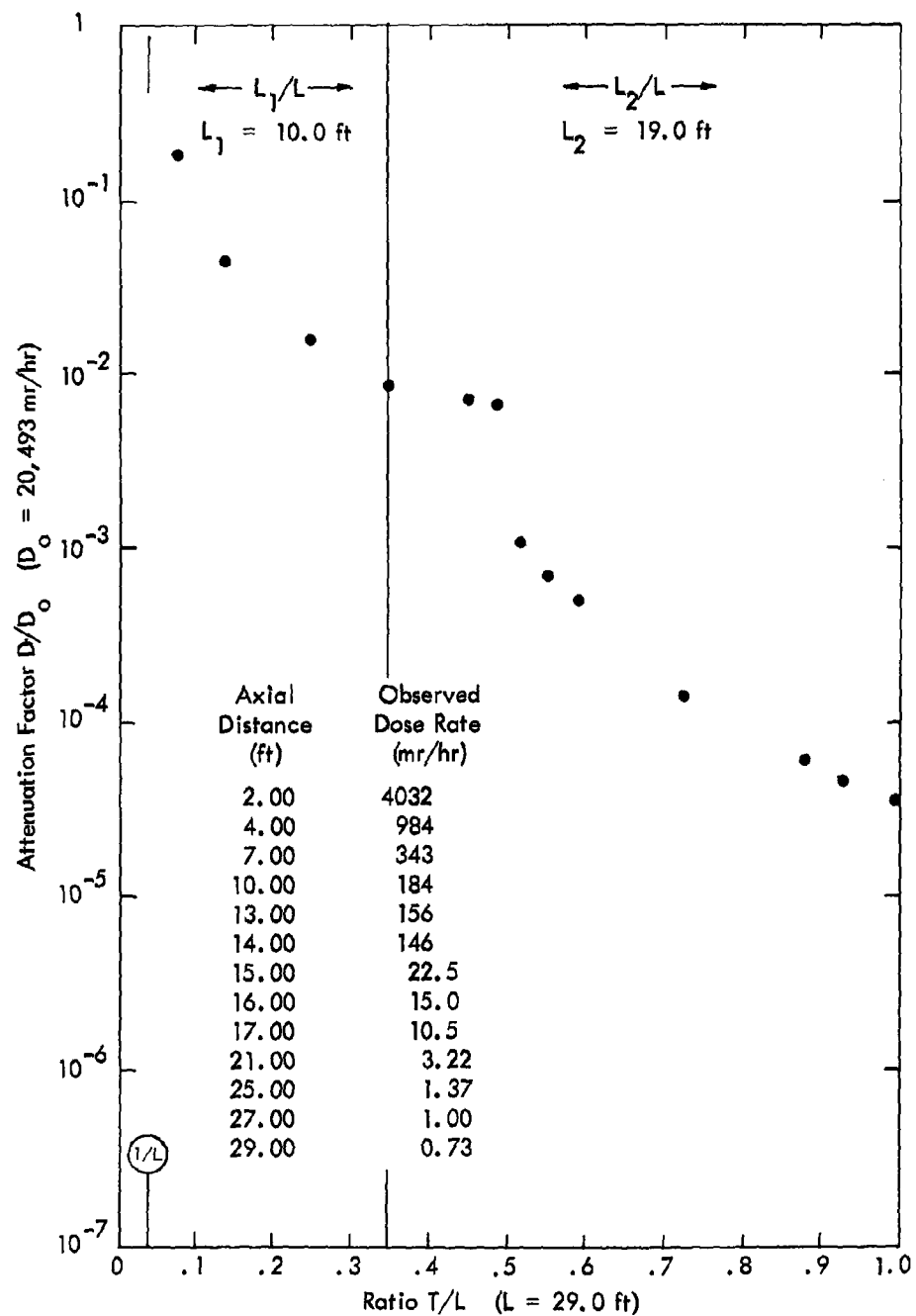
Figure 15. L-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 8.1-curie Au^{198} point source. (From Reference 3, Table 6.)
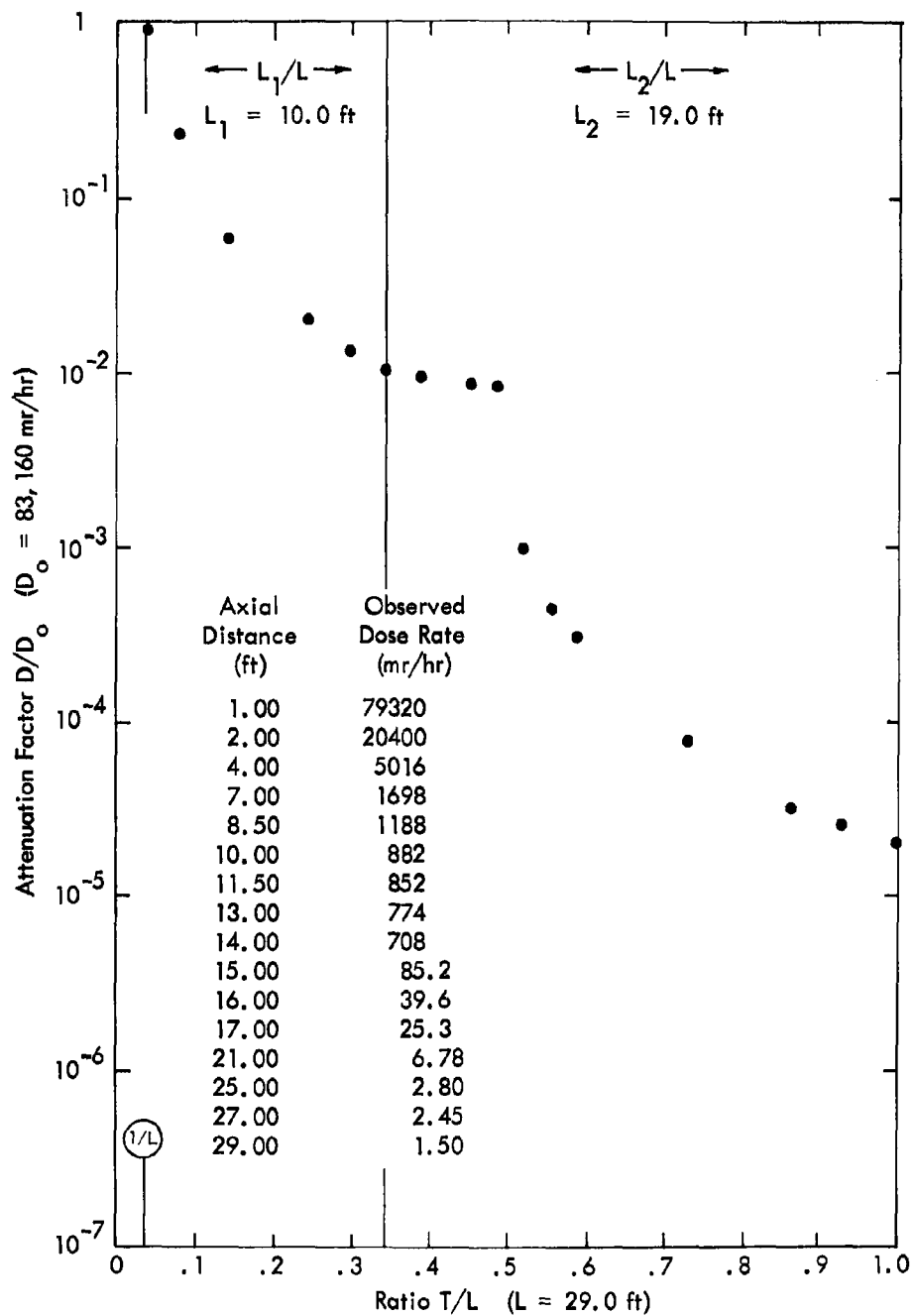
L_1/L $L_1 = 13.0$ ft

L_2/L $L_2 = 14.0$ ft

L_3/L $L_3 = 10.0$ ft

Attenuation Factor D/D_o ($D_o = 710,000$ mr/hr)

Axial Distance (ft)	Observed Dose Rate (mr/hr)
4.00	54000
6.00	24630
8.00	13572
10.00	9090
11.50	7524
13.00	5839
14.50	5952
17.00	4687
18.00	474
20.00	190
22.00	105
24.00	61.0
26.00	37.2
27.00	34.9
28.00	36.0
29.00	36.6
30.00	31.4
31.00	25.1
32.00	12.6
33.00	3.31
34.00	2.37
35.00	1.68
36.00	1.24
37.00	1.00
41.00	0.37

1/L

Ratio T/L   (L = 37.0 ft)

Figure 16.   Z-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 50-curie Co^{60} point source. (From Reference 4, Table 1.)
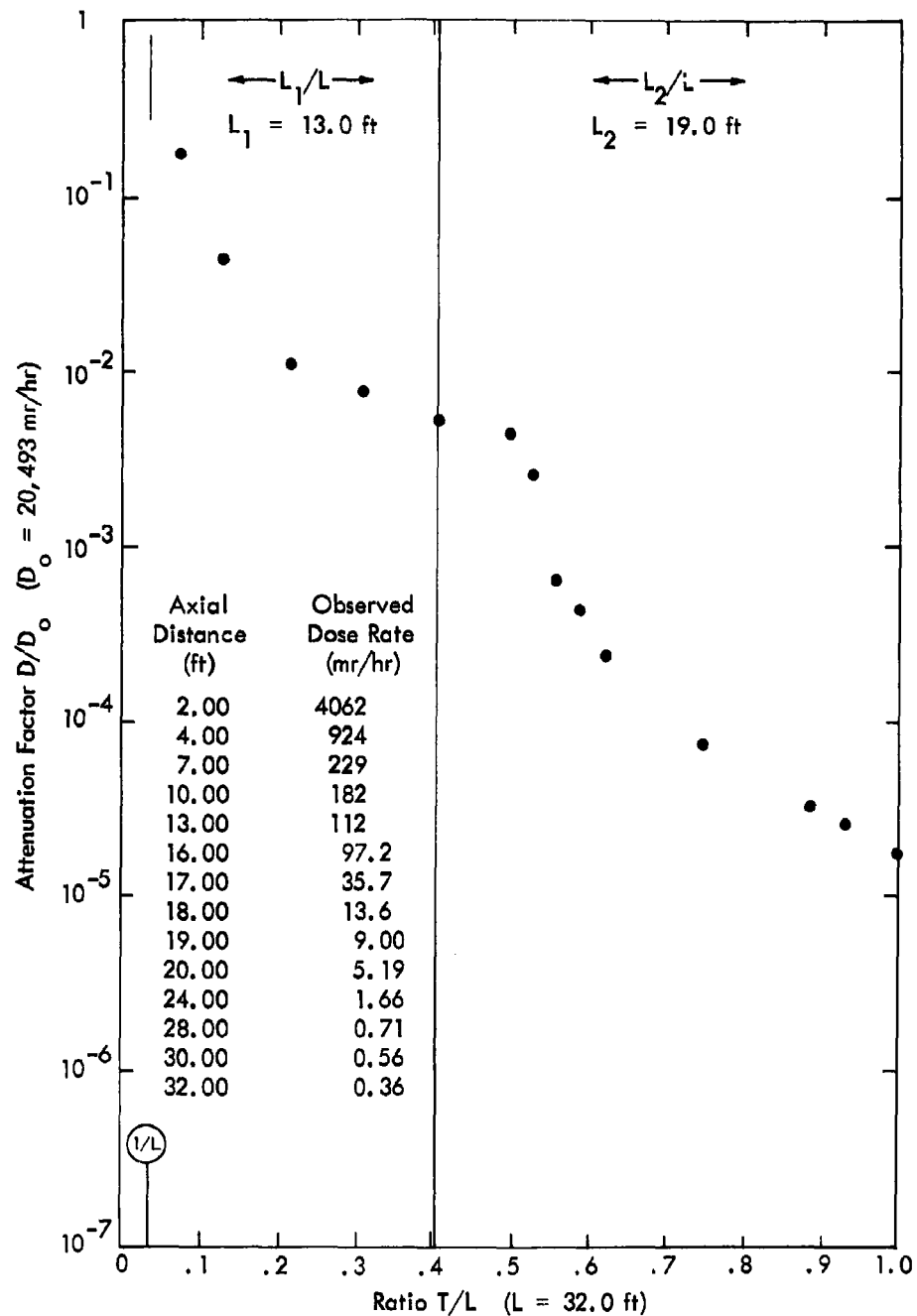
27

The plot contains the following data table:

Axial Distance (ft)	Observed Dose Rate (mr/hr)
4.00	24492
6.00	10356
8.00	6300
10.00	4284
11.50	3061
13.00	2376
16.00	2067
17.00	1978
18.00	267
20.00	115
22.00	60.8
24.00	33.1
26.00	24.1
27.00	20.3
28.00	20.6
29.00	18.2
30.00	17.3
31.00	14.1
32.00	7.56
33.00	1.99
34.00	1.44
35.00	1.02
36.00	0.76
37.00	0.61
41.00	0.26

Plot axis labels: Attenuation Factor D/D_o (D_o = 275,200 mr/hr) versus Ratio T/L (L = 37.0 ft). Region labels: L_1/L, L_1 = 13.0 ft; L_2/L, L_2 = 14.0 ft; L_3/L, L_3 = 10.0 ft.

Figure 17. Z-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 80-curie Cs[137] point source. (From Reference 4, Table 2.)

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Figure 18. U-shaped 6 x 6-foot concrete entranceway with $W/2 = 3.0$ feet; 50-curie Co^{60} point source. (From Reference 4, Table 3.)
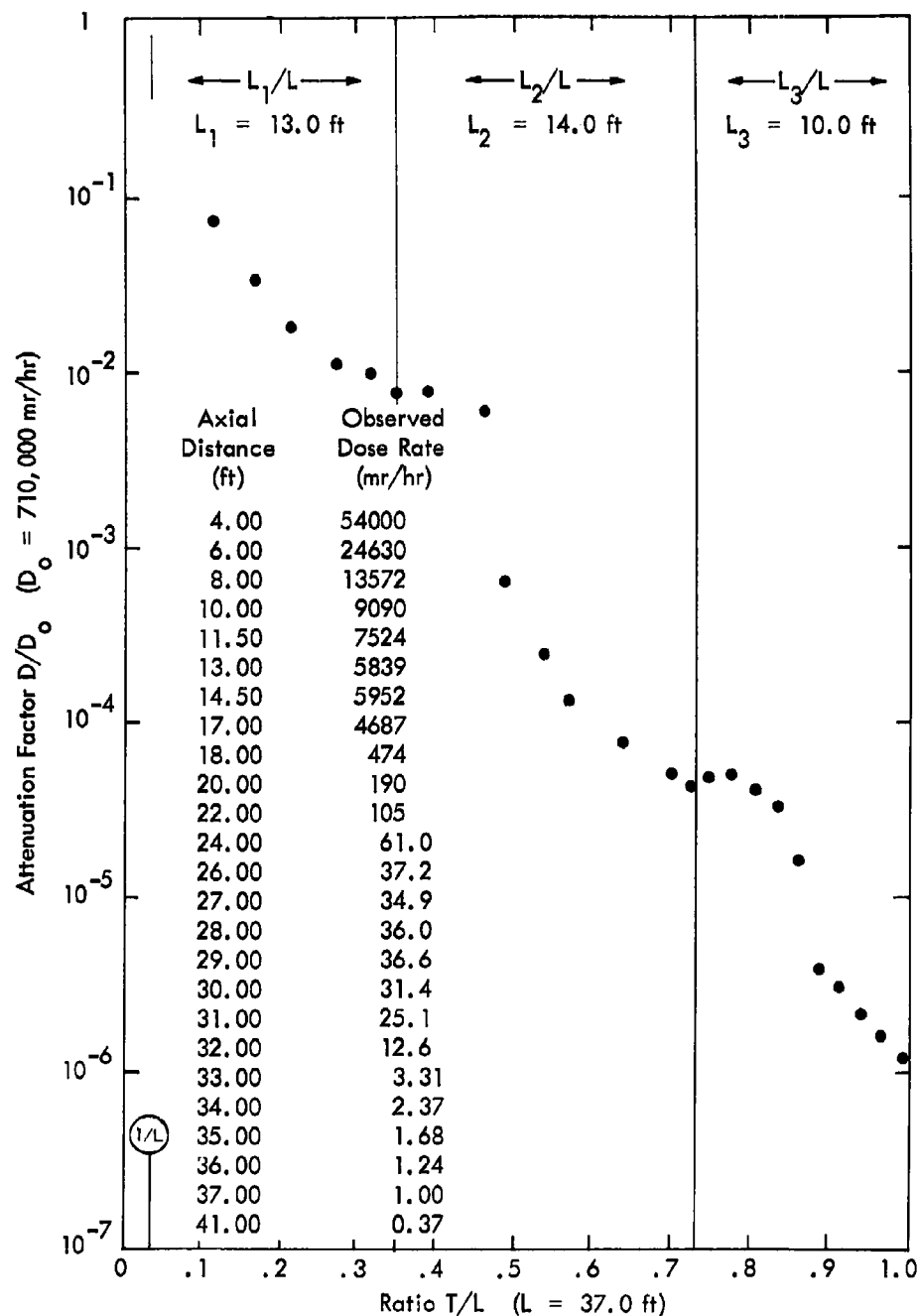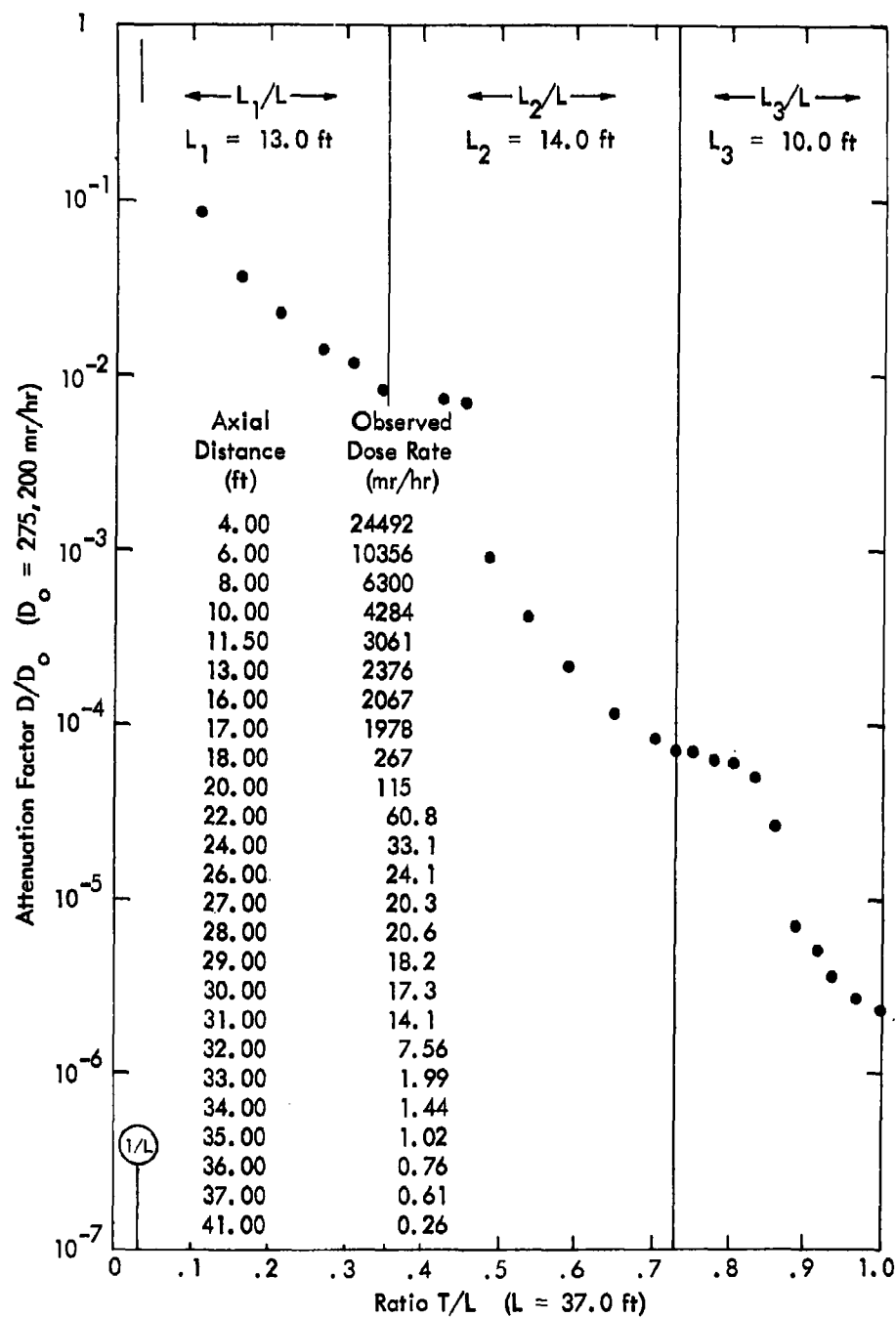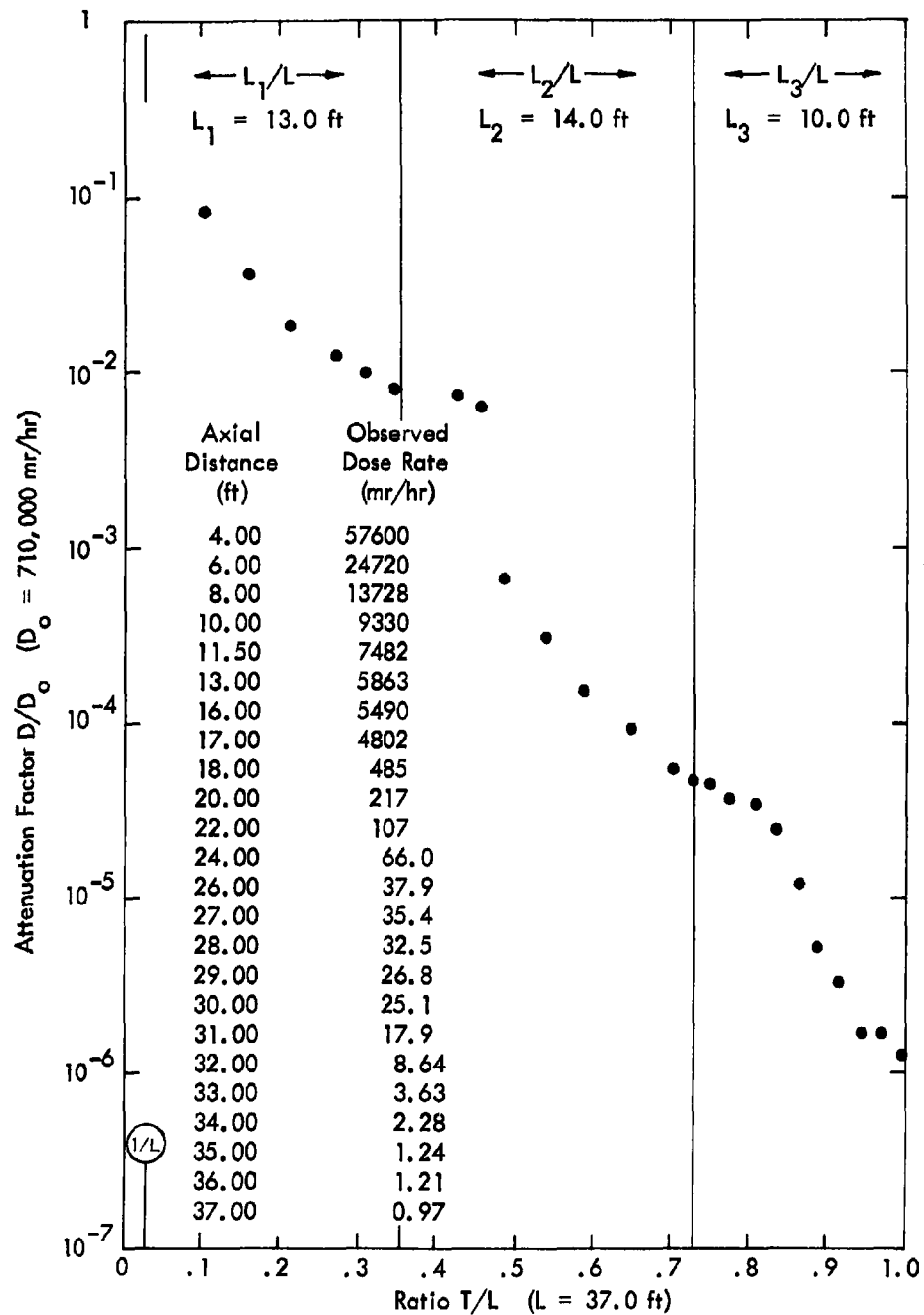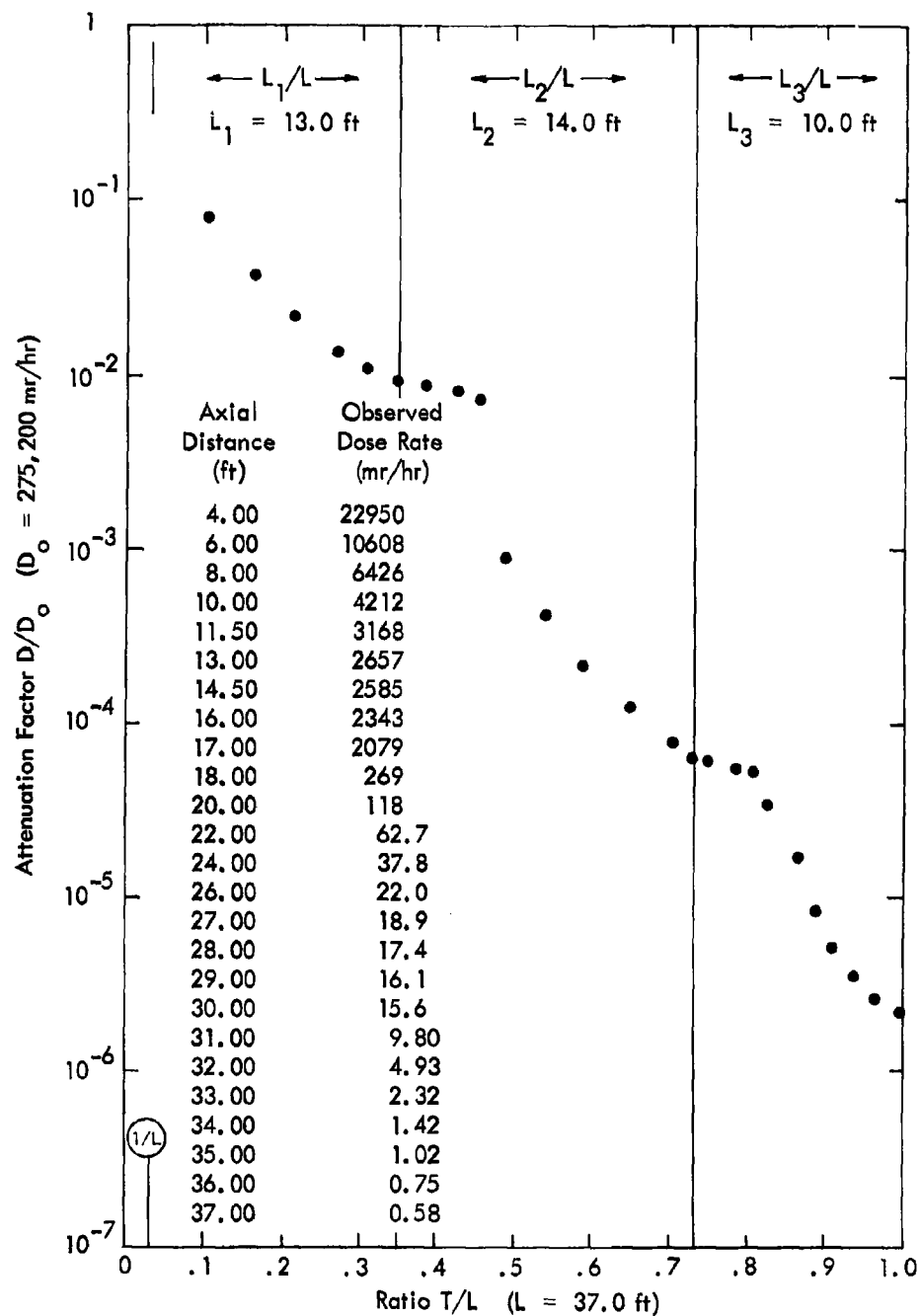
$\leftarrow L_1/L \rightarrow$ $\leftarrow L_2/L \rightarrow$ $\leftarrow L_3/L \rightarrow$

$L_1 = 13.0$ ft $L_2 = 14.0$ ft $L_3 = 10.0$ ft

Attenuation Factor D/D_o ($D_o = 275,200$ mr/hr)

Axial Distance (ft)	Observed Dose Rate (mr/hr)
4.00	22950
6.00	10608
8.00	6426
10.00	4212
11.50	3168
13.00	2657
14.50	2585
16.00	2343
17.00	2079
18.00	269
20.00	118
22.00	62.7
24.00	37.8
26.00	22.0
27.00	18.9
28.00	17.4
29.00	16.1
30.00	15.6
31.00	9.80
32.00	4.93
33.00	2.32
34.00	1.42
35.00	1.02
36.00	0.75
37.00	0.58

(1/L)

Ratio T/L   (L = 37.0 ft)

Figure 19. U-shaped 6 x 6-foot concrete entranceway with W/2 = 3.0 feet; 80-curie Cs[137] point source. (From Reference 4, Table 4.)

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$\leftarrow L_1/L \rightarrow$ $\leftarrow L_2/L \rightarrow$ $\leftarrow L_3/L \rightarrow$

$L_1 = 3.5$ ft $L_2 = 4.0$ ft $L_3 = 3.5$ ft

Attenuation Factor D/D_o ($D_o = 710,000$ mr/hr)

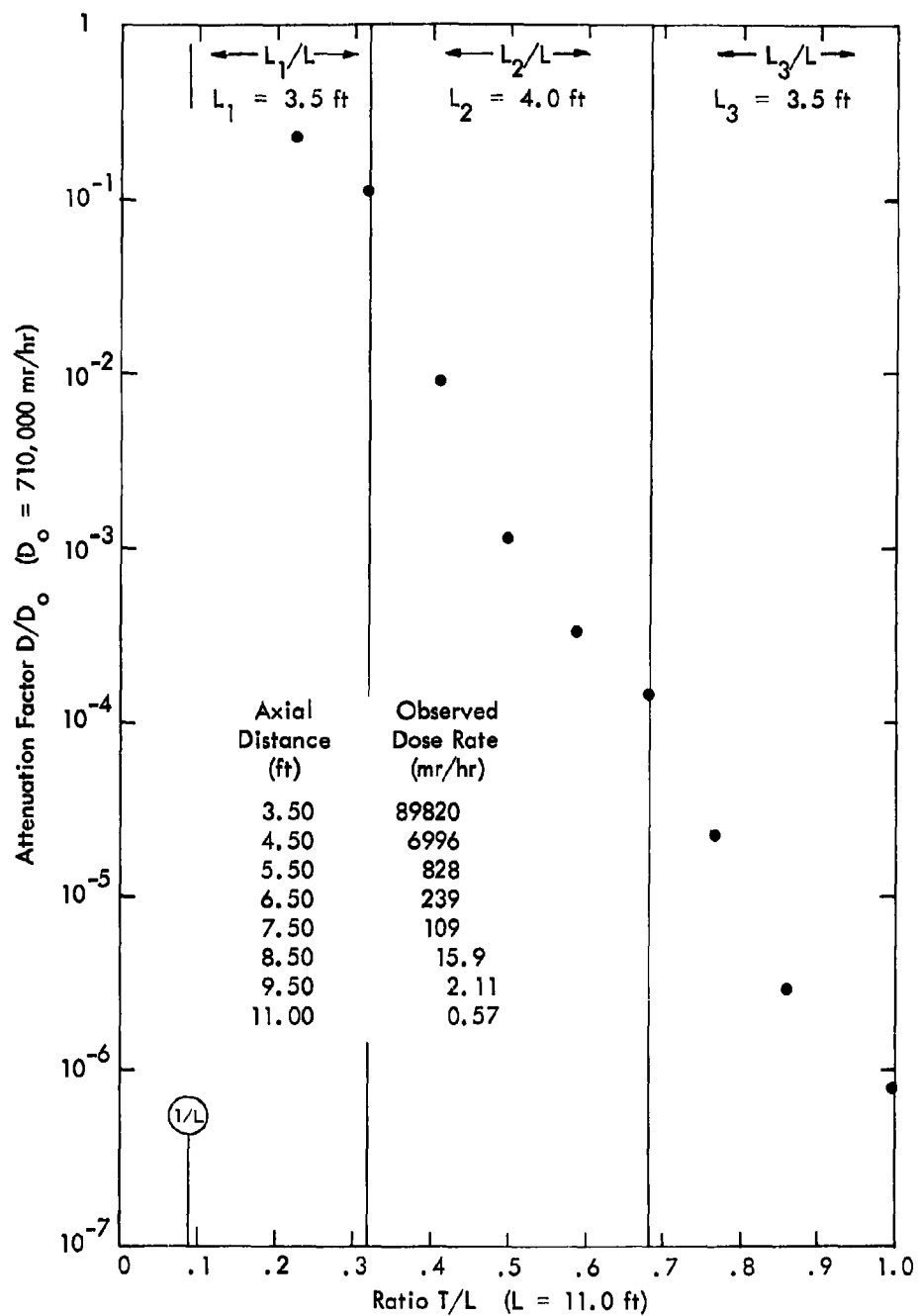| Axial Distance (ft)	Observed Dose Rate (mr/hr)
3.50	89820
4.50	6996
5.50	828
6.50	239
7.50	109
8.50	15.9
9.50	2.11
11.00	0.57

1/L

Ratio T/L (L = 11.0 ft)

Figure 20. Z-shaped 1 x 1-foot concrete entranceway with
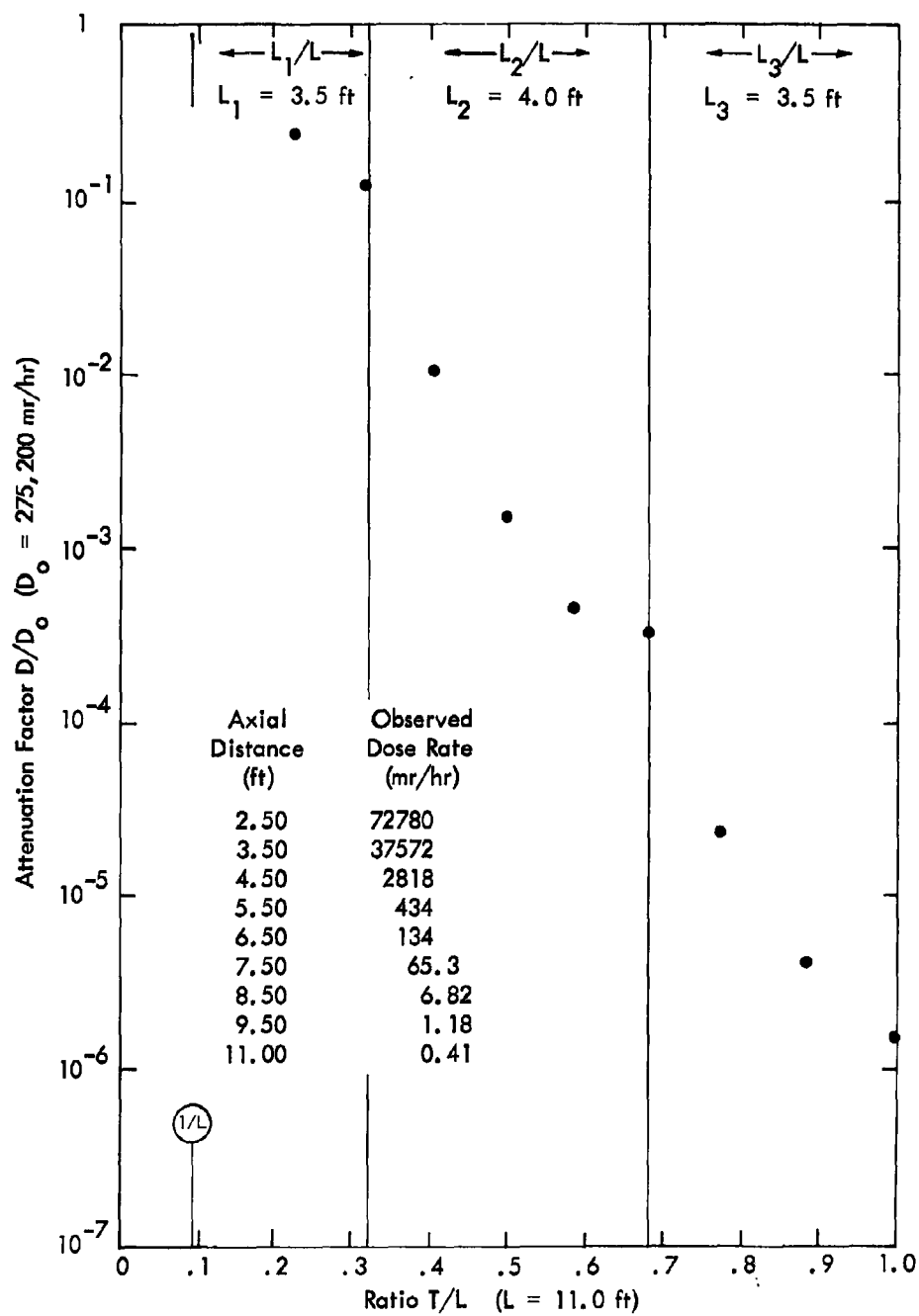W/2 = 0.5 foot; 50-curie Co^{60} point source.
(From Reference 4, Table 6.)

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Figure 21. Z-shaped 1 x 1-foot concrete entranceway with W/2 = 0.5 foot; 80-curie Cs[137] point source. (From Reference 4, Table 7.)

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The figure shows:

- Y-axis: Attenuation Factor D/D_o ($D_o = 710{,}000$ mr/hr), logarithmic scale from 10^{-7} to 1.
- X-axis: Ratio T/L (L = 13.0 ft), from 0 to 1.0.
- Top labels: L_1/L, $L_1 = 3.5$ ft; L_2/L, $L_2 = 4.0$ ft; L_3/L, $L_3 = 5.5$ ft.
- A circled label "1/L".

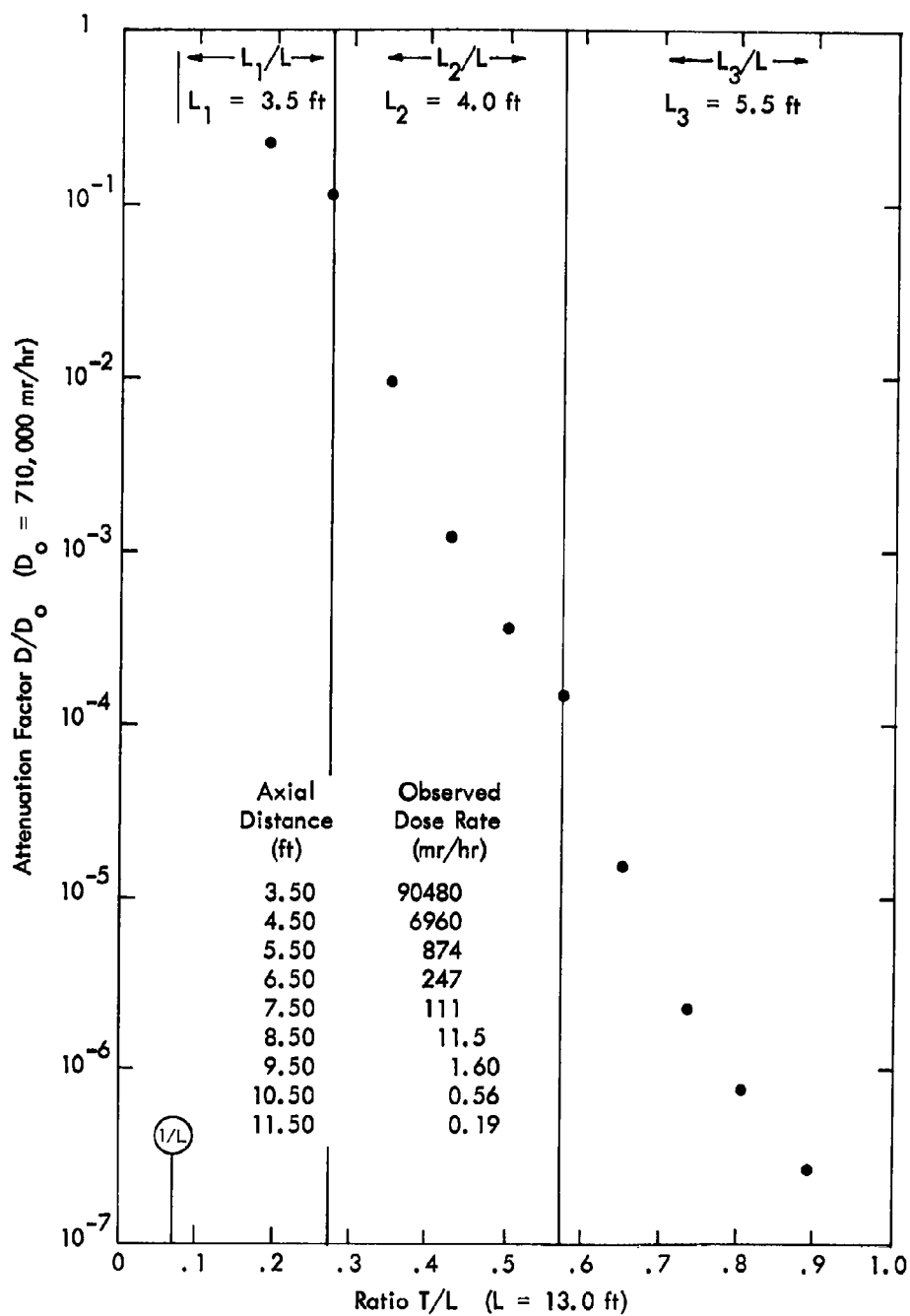| Axial Distance (ft)	Observed Dose Rate (mr/hr)
3.50	90480
4.50	6960
5.50	874
6.50	247
7.50	111
8.50	11.5
9.50	1.60
10.50	0.56
11.50	0.19

Figure 22. U-shaped 1 x 1-foot concrete entranceway with W/2 = 0.5 foot; 50-curie Co^{60} point source. (From Reference 4, Table 8.)
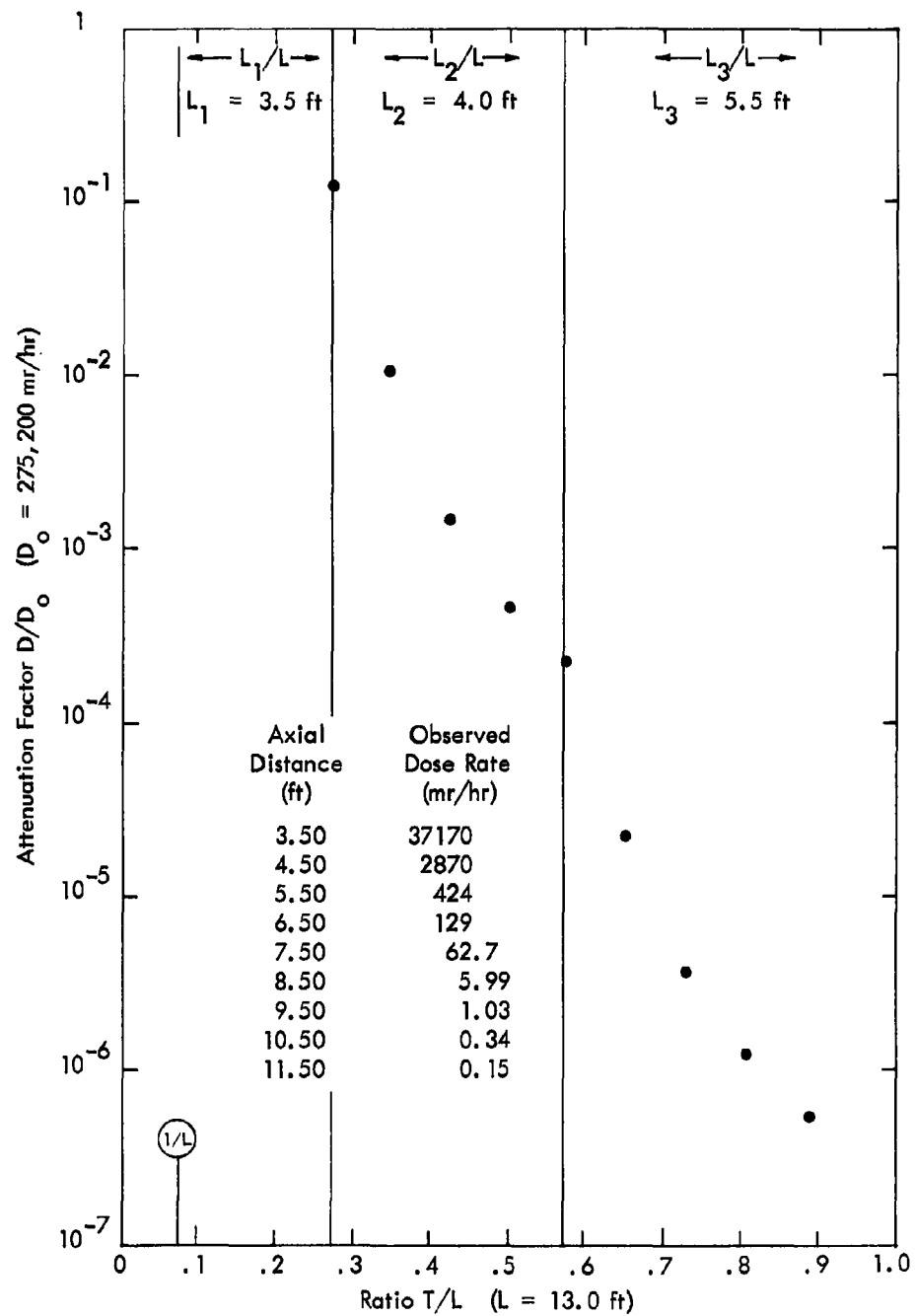
33

Figure 23. U-shaped 1 x 1-foot concrete entranceway with W/2 = 0.5 foot; 80-curie Cs^{137} point source. (From Reference 4, Table 9.)
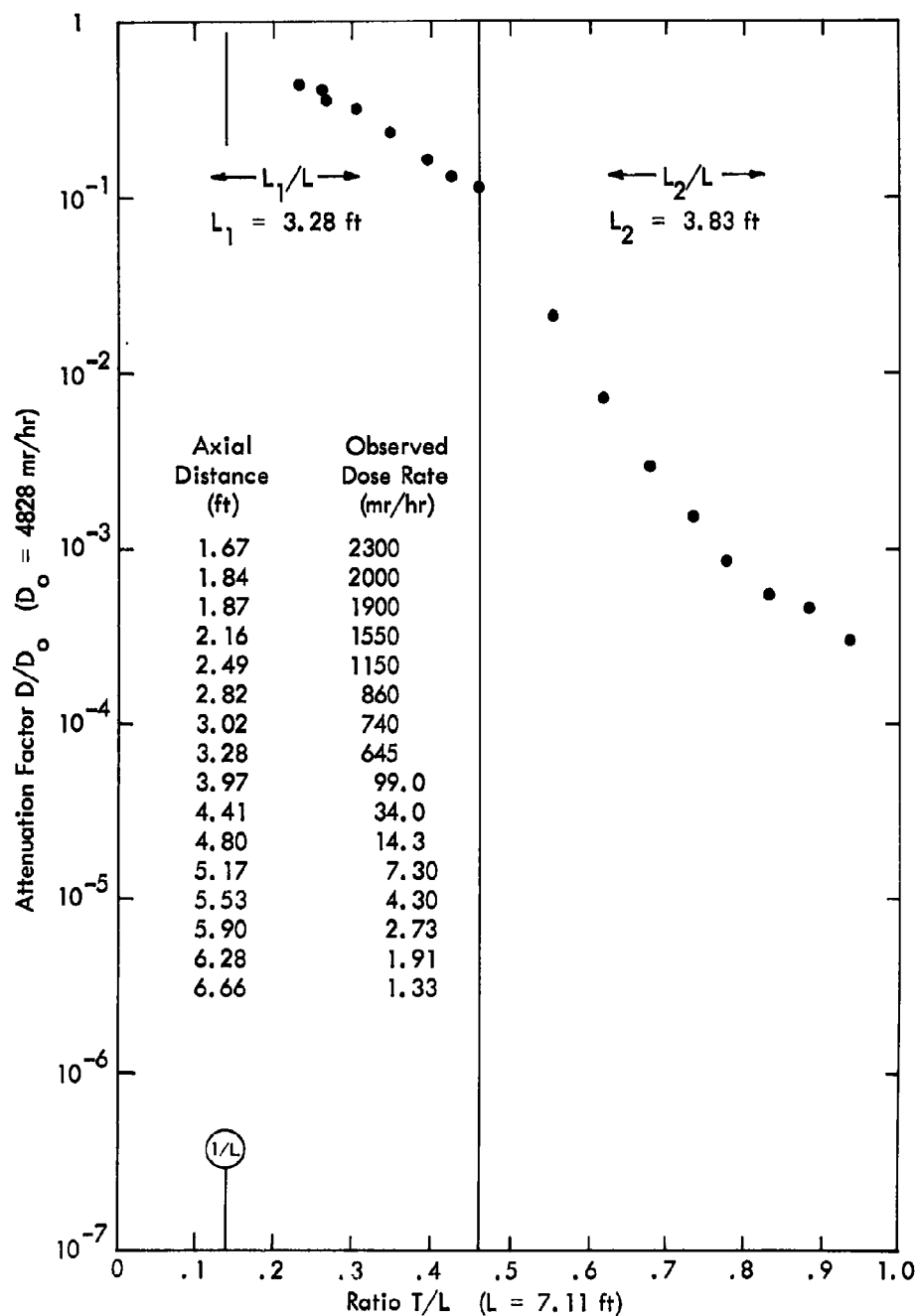
34

Figure 24. L-shaped 0.9167 x 0.9167-foot square concrete duct with W/2 = 0.4583 foot; 0.34-curie Co[60] point source. Source in corner for L_1 measurements. (From Reference 5, Figure 12 and Table 8C-C.)
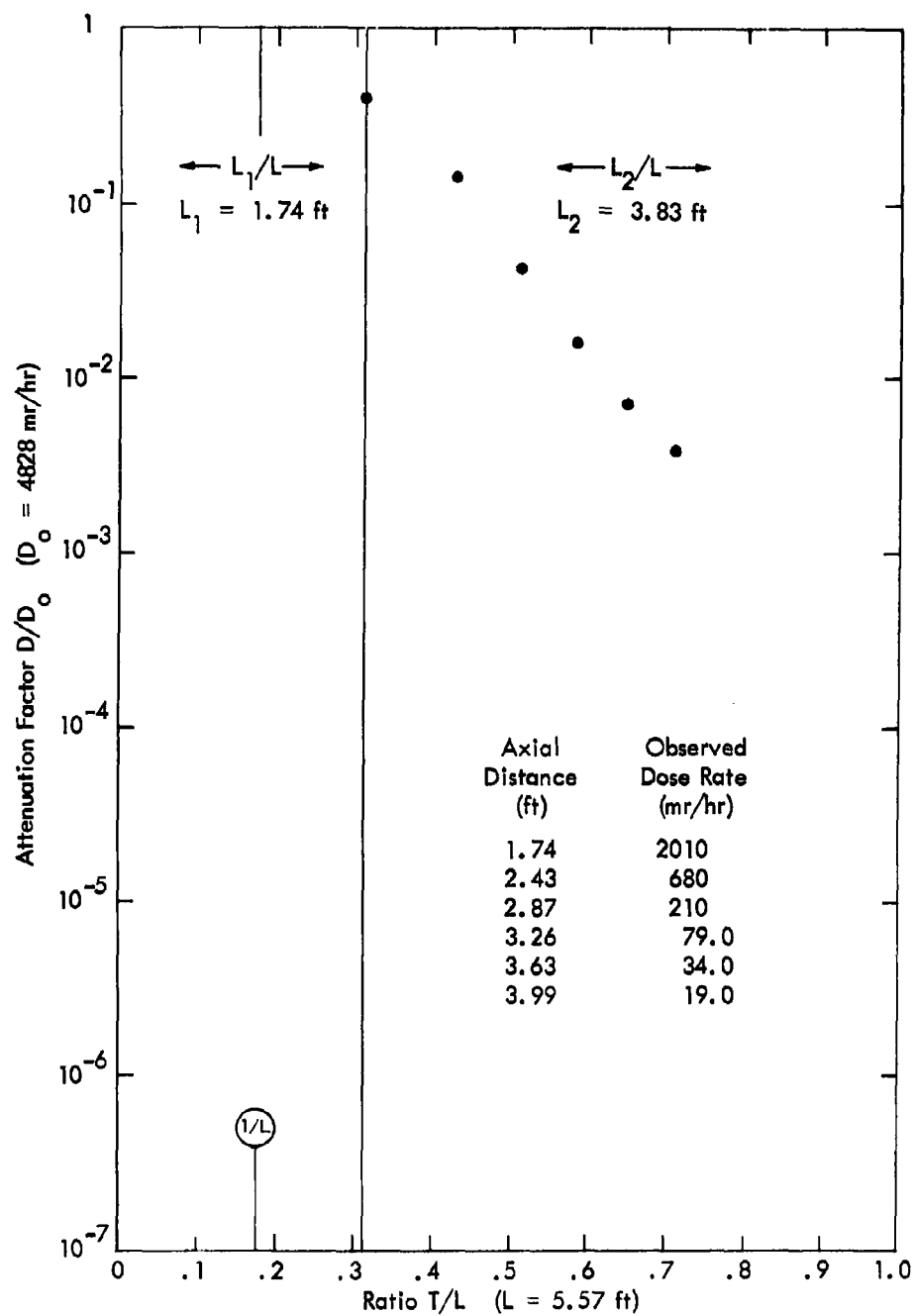
Figure 25. L-shaped 0.9167 x 0.9167-foot square concrete duct with W/2 = 0.4583 foot; 0.34-curie Co^{60} point source. (From Reference 5, Table 10C-C.)

Graph content:

Y-axis: Attenuation Factor D/D$_o$ (D$_o$ = 4828 mr/hr), scale from 10^{-7} to 1

X-axis: Ratio T/L (L = 5.57 ft), scale from 0 to 1.0

L$_1$/L   L$_2$/L
L$_1$ = 1.74 ft   L$_2$ = 3.83 ft

1/L

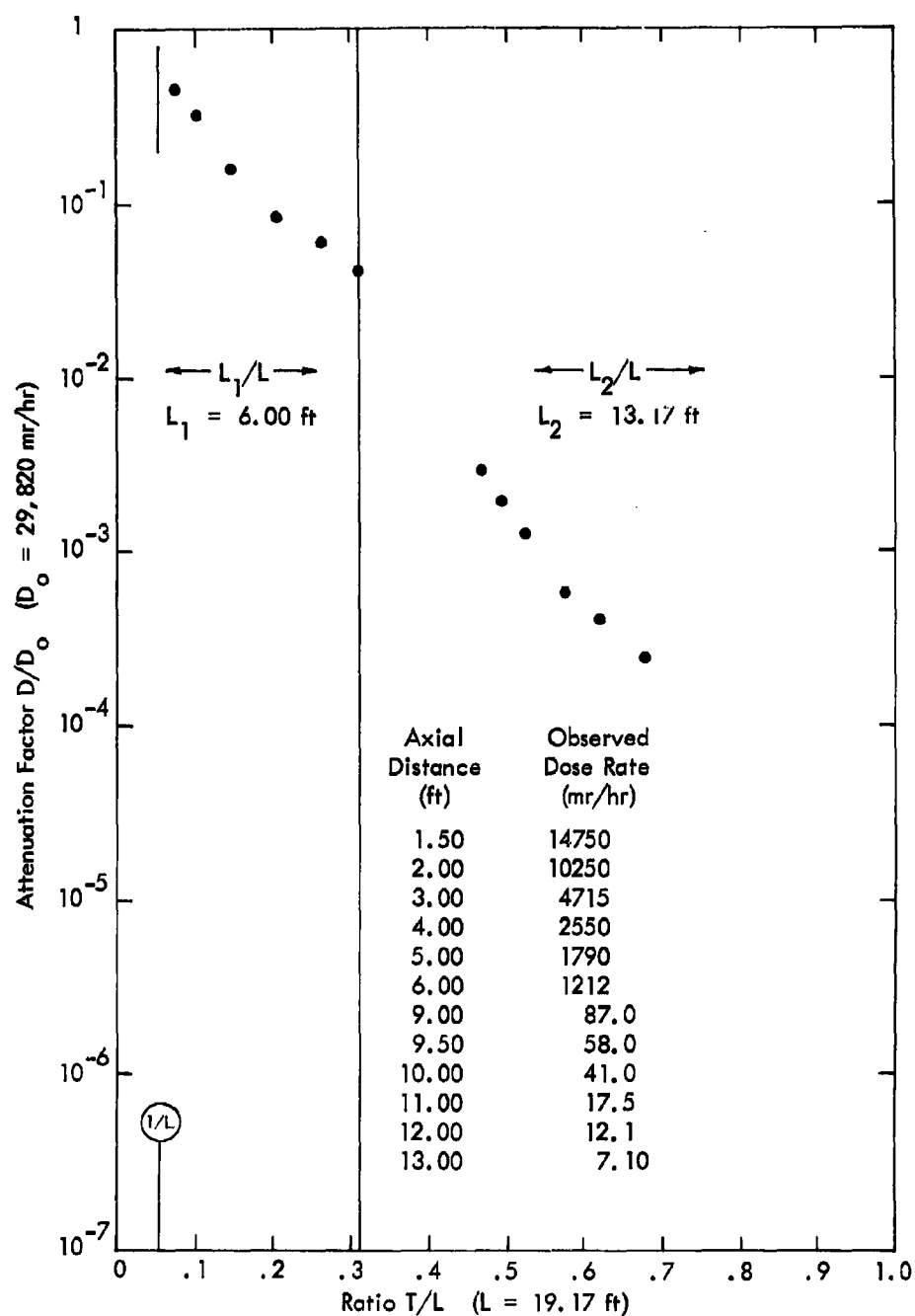| Axial Distance (ft)	Observed Dose Rate (mr/hr)
1.74	2010
2.43	680
2.87	210
3.26	79.0
3.63	34.0
3.99	19.0

Figure 26. L-shaped 3 x 3-foot square concrete entranceway with W/2 = 1.5 feet; 2. 1-curie Co^{60} point source. (From Reference 6, Table IA.)

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Figure with axis labels and embedded data table.

Attenuation Factor D/D_o (D_o = 29,820 mr/hr)

L_1/L L_1 = 7.50 ft

L_2/L L_2 = 13.17 ft

Axial Distance (ft)	Observed Dose Rate (mr/hr)
3.50	3320
4.00	2460
4.50	1950
6.00	1150
7.50	729
9.50	200
10.00	74.0
10.50	38.0
11.00	31.0
12.00	13.5
13.00	9.10
13.50	6.40
15.00	3.70

1/L

Ratio T/L   (L = 20.67 ft)
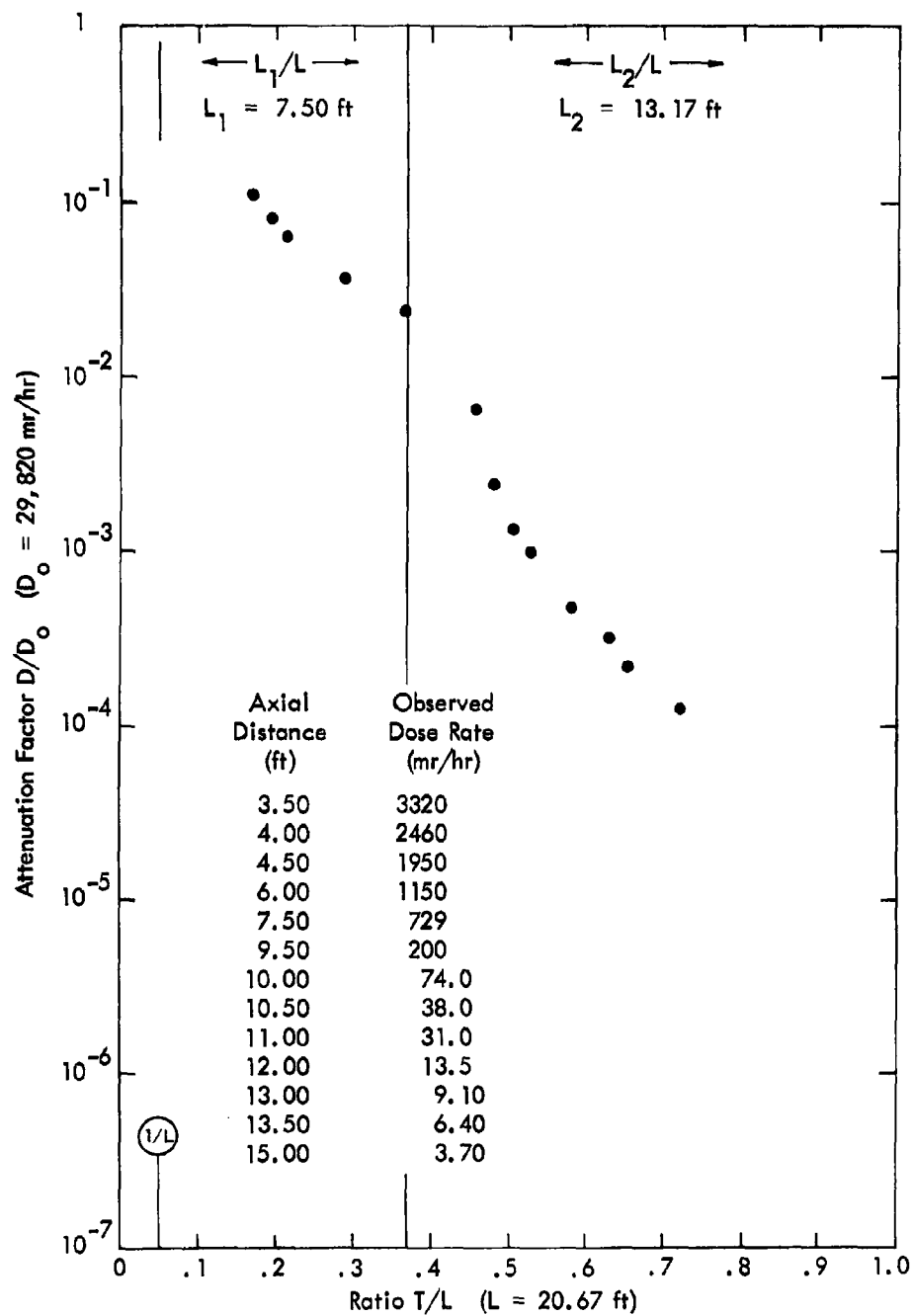
Figure 27.   L-shaped 3 x 3-foot square concrete entranceway with W/2 = 1.5 feet; 2.1-curie Co^{60} point source. (From Reference 6, Table IB.)
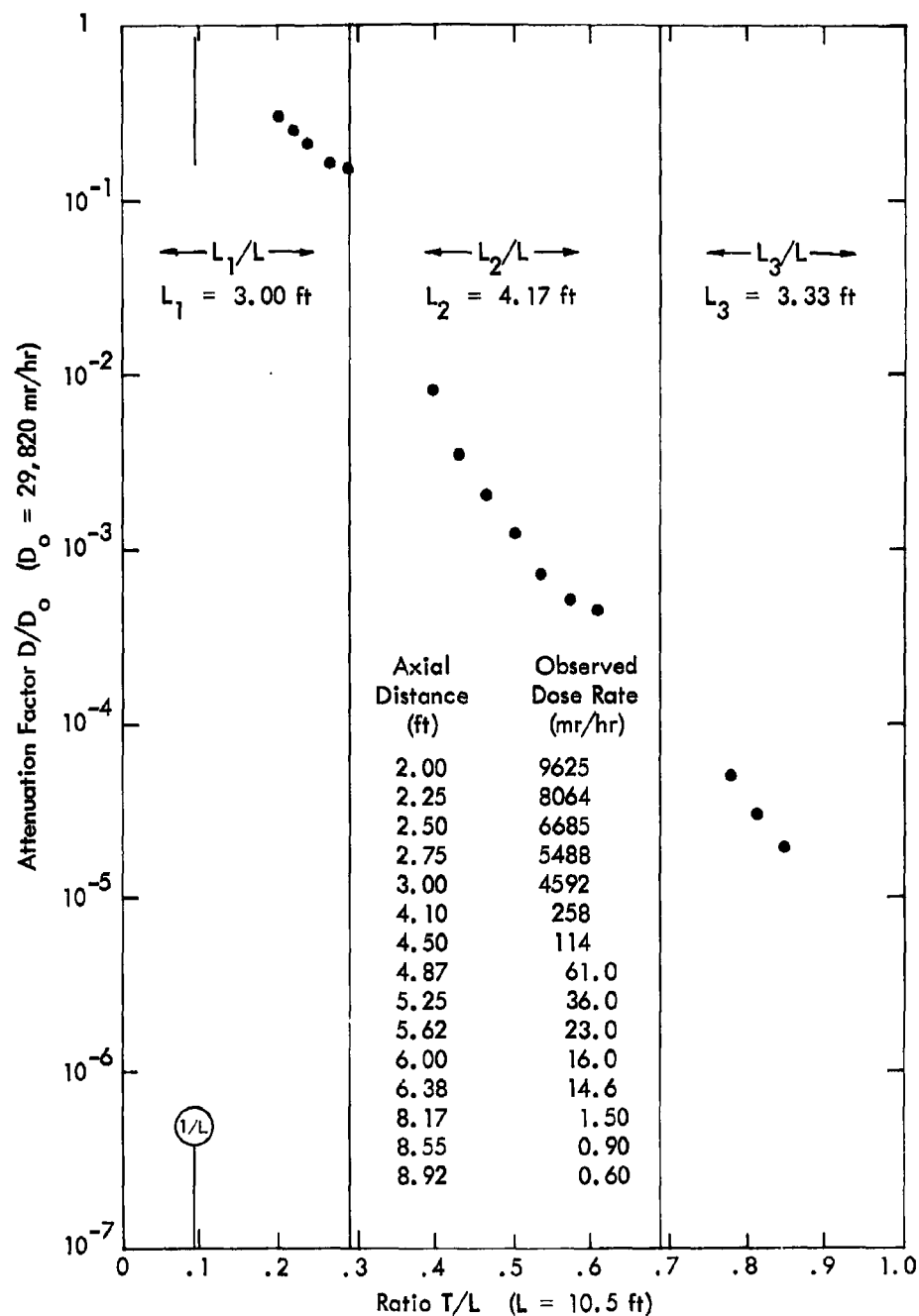
1

10^{-1}

10^{-2}

10^{-3}

10^{-4}

10^{-5}

10^{-6}

10^{-7}

Attenuation Factor D/D_o (D_o = 29,820 mr/hr)

←—L_1/L—→
L_1 = 3.00 ft

←—L_2/L—→
L_2 = 4.17 ft

←—L_3/L—→
L_3 = 3.33 ft

1/L

Axial Distance (ft)	Observed Dose Rate (mr/hr)
2.00	9625
2.25	8064
2.50	6685
2.75	5488
3.00	4592
4.10	258
4.50	114
4.87	61.0
5.25	36.0
5.62	23.0
6.00	16.0
6.38	14.6
8.17	1.50
8.55	0.90
8.92	0.60

0   .1   .2   .3   .4   .5   .6   .7   .8   .9   1.0

Ratio T/L   (L = 10.5 ft)

Figure 28.   Z-shaped 1-foot-diameter round concrete duct with
W/2 = 0.443 foot; 2.1-curie Co60 point source;
0.3-curie source used for L_1 (D/7 = actual dose).
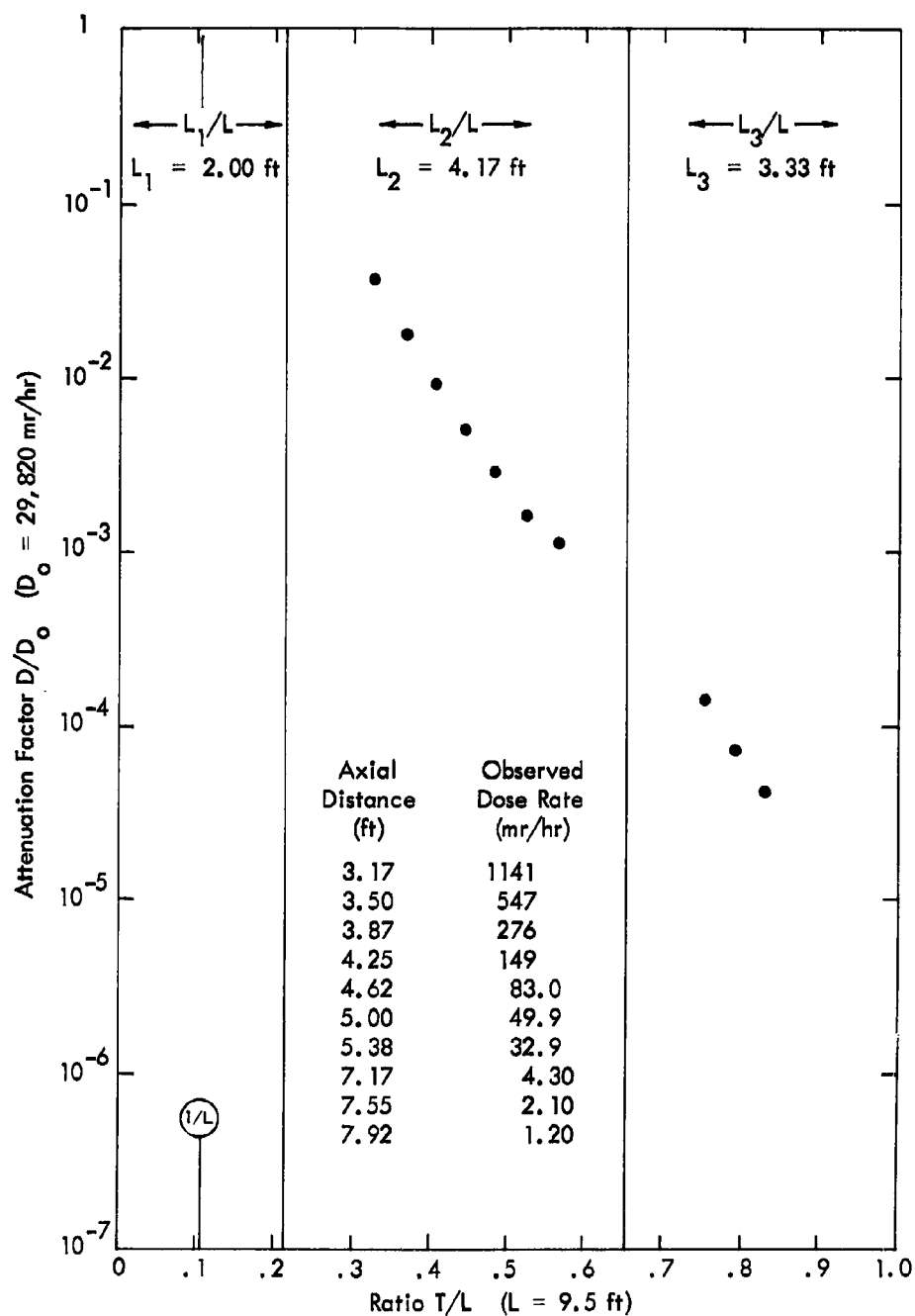(From Reference 7, Tables I, III, IV.)

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Figure 29. Z-shaped 1-foot-diameter round concrete duct with W/2 = 0.443 foot; 2.1-curie Co^{60} point source. (From Reference 7, Tables III, IV.)
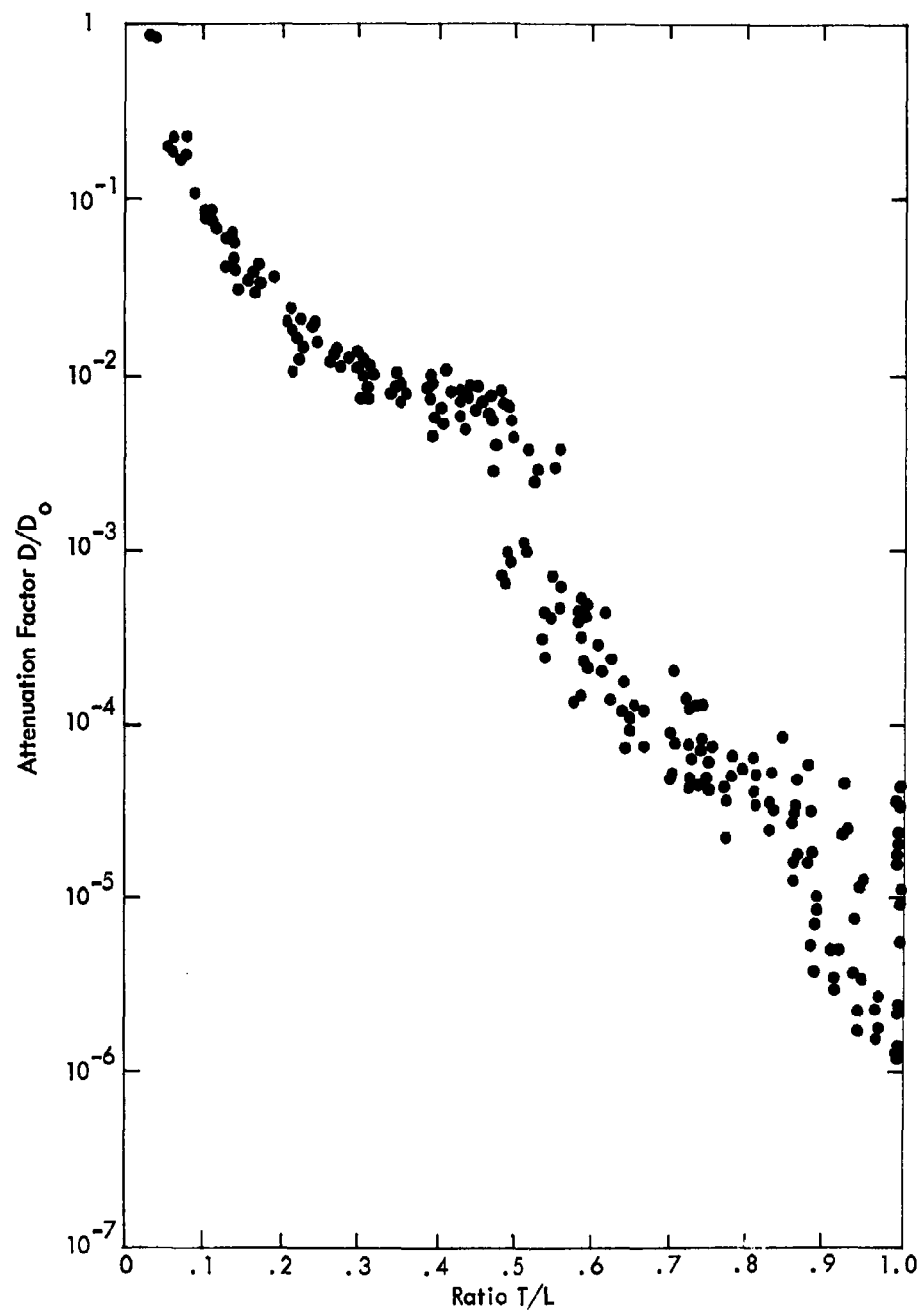
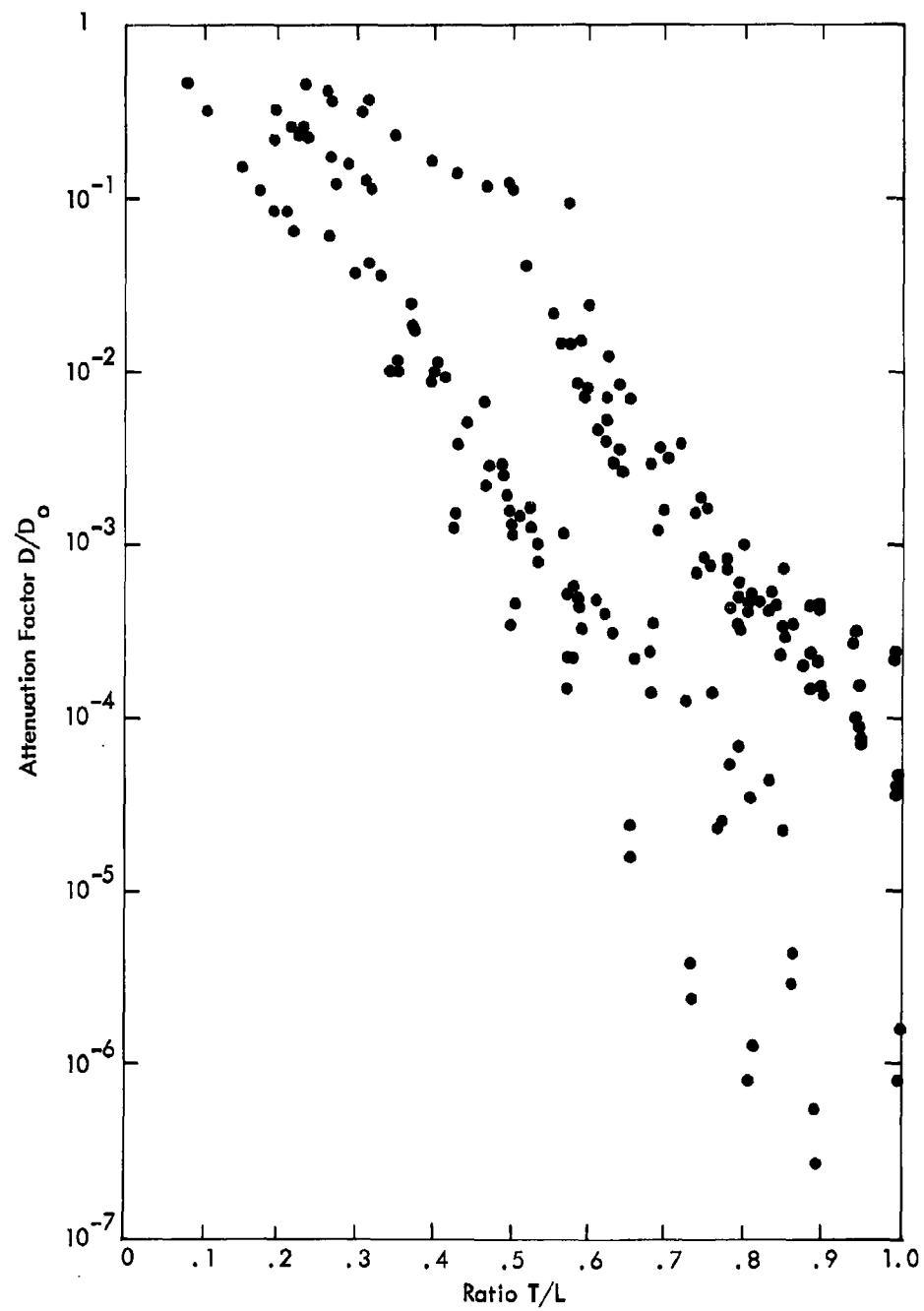Figure 30. Attenuation factor vs ratio T/L for 6 x 6-foot ducts.

Figure 31.   Attenuation factor vs ratio T/L for other than
6 x 6-foot ducts.

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